Enabling Technologies for Increasing Renewable Energy Penetration in Isolated Power Systems

By

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Statements and Declarations

Declaration of Originality

This thesis contains no material which has been accepted for a degree or diploma by the University of Tasmania or any other institution, except by way of background information and of which is duly acknowledged in the thesis. To the best of my knowledge and belief, this thesis contains no material previously published or written by another person except where due acknowledgement is made in the text of the thesis, nor does the thesis contain any material that infringes copyright. I have also acknowledged, where appropriate, the specific contributions made by co-authors of published and submitted manuscripts.

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Statement of Co-Authorship

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Papers and Presentations at Scientific Conferences that Relate to This Thesis

The following papers relate specifically to this thesis and were presented at national and/or international scientific conferences during the period of candidature.

M. deGroot, J. Forbes, and **D. Nikolic**, "Demand response in Isolated Power Systems," in *2013 Australasian Universities Power Engineering Conference (AUPEC)*, Hobart, Australia 2013, pp. 1-6 [1].

Dusan Nikolic, Michael Negnevitsky, Martin deGroot, "The Smart Grid: Enabling Demand Response," presented at the The Fifth International Conference on Smart Grids, Green Communications and IT Energy-aware Technologies ENERGY 2015, Rome, Italy, 2015 [2].

D. Nikolic, M. Negnevitsky, M. deGroot, S. Gamble, J. Forbes, and M. Ross, "Fast demand response as an enabling technology for high renewable energy penetration in isolated power systems," in *2014 IEEE PES General Meeting | Conference & Exposition*, Washington DC, USA 2014, pp. 1-5 [3].

M. N. **Dusan Nikolic**, Martin deGroot, "Effect of the Diesel Engine Delay on Frequency Stability of Isolated Power Systems with High Levels of Renewable Energy Penetration," presented at the 2015 International Symposium on Smart Electric Distribution Systems and Technologies (EDST), *CIGRE SC C6 Colloquium*, Vienna, Austria, 2015 [4].

Dusan Nikolic, Brendon Bateman, Chris Blanksby, “Age of renewable power systems – Transformation of island power systems”, *25th PPA Conference & Trade Exhibition* and 8th Engineers’ Workshop, Nuku’alofa, Kingdom of Tonga, August 1 – 5, 2016, 25th Annual Conference & Trade Exhibition.

Dusan Nikolic, Chris Blanksby, “Age of renewable power systems – How to avoid pitfalls in transitioning to green energy?”, *25th PPA Conference & Trade Exhibition* and 8th Engineers’ Workshop, Nuku’alofa, Kingdom of Tonga, August 1 – 5, 2016, 8th Engineers’ Workshop.

Negnevitsky M, deGroot M., **Nikolic Dusan**, Simon Gamble, James Forbes, Michael Ross, "Fast demand response as an enabling technology for high renewable energy penetration in isolated power systems," in *Cigre Session 2016*, Paris, France, 2016 [5].

D. Nikolic, M. Negnevitsky, and M. deGroot, "Fast demand response as spinning reserve in microgrids," in *Mediterranean Conference on Power Generation, Transmission, Distribution and Energy Conversion (MedPower 2016)*, 2016, pp. 1-5 [6].

Dusan Nikolic, Chris Blanksby, Tangi Tereapii, Woo Yul Lee, "Cook Islands: Planning 100% Renewable Energy in Different Guises", presented at *REM 2016: Renewable Energy integration with Mini/Microgrid*, Applied Energy Symposium and Forum 2016, April 19th-21st 2016, Maldives, published in Energy Procedia, Volume 103, December 2016, Pages 207-212.

Dusan Nikolic, Michael Negnevitsky, "Practical Solution for the Low Inertia Problem in High Renewable Penetration Isolated Power systems", Conference Proceedings, *IEEE Power Energy Society General Meeting*, August 5-9, Portland USA 2018 [7].

Dusan Nikolic, Michael Negnevitsky, "Smart Grid in Isolated Power Systems – Practical Operational Experiences", Conference Proceedings, Applied Energy Symposium and Forum, *Renewable Energy Integration with Mini/Microgrids, REM 2018*, 29–30 September 2018, Rhodes, Greece [8].

Dusan Nikolic, Michael Negnevitsky, "Adding Inertia to Isolated Power Systems for 100% Renewable Operation", Conference Proceedings, Applied Energy Symposium and Forum, *Renewable Energy Integration with Mini/Microgrids, REM 2018*, 29–30 September 2018, Rhodes, Greece [9].

Abbreviations used in the Thesis

AC	-	Alternating current
DC	-	Direct current
GDP	-	Gross Domestic Product
GHG	-	Green-house gasses
GW	-	Giga watt
HV	-	High Voltage
IPS	-	Isolated Power System
kW	-	Kilo watt
kWh	-	Kilo watt hour
LCOE	-	Levelised cost of energy
LV	-	Low voltage
MW	-	Mega watt
MVAR	-	Mega volt-ampere reactive (reactive power)
O&M	-	Operation and Maintenance
RE	-	Renewable Energy
SAIDI	-	System Average Interruption Duration Index
SAIFI	-	System Average Interruption Frequency Index
SC	-	Synchronous Condenser
WiMAX	-	Worldwide Interoperability for Microwave Access
ZigBee	-	An IEEE 802.15.4-based specification for a wireless protocol

Terms used in the Thesis

Renewable energy **penetration** – term used in this thesis to denote instantaneous amount of renewable **power** in the system as a percentage of the total power system load.

Renewable energy **contribution** – term used in this thesis to denote annual amount of renewable **energy** in the system as a percentage of the total annual energy demand.

Abstract

Isolated Power Systems supply electric energy to customers living in remote areas across the world. Traditionally, electric energy in IPSs is produced using diesel generators, which are convenient, but produce several problems for the isolated communities such as high cost of electric energy, high amount of GHG emissions, and they force isolated communities into an energy dependence from other communities or nations.

Renewable energy technologies offer some of the solutions to the problems isolated communities face as they often produce energy at a lower cost than diesel generators, they provide energy independence as local energy resources are used and produce very small amount or no polluting emissions at all. Renewable energy generation also brings challenges to the isolated communities, such as lowered power system stability. Renewable energy generation in IPSs is therefore often paired with enabling technologies, which allow it to generate reliable emissions-free power.

Defining appropriate enabling technologies which facilitate cost-effective high renewable energy generation in IPSs is the primary goal of this Thesis. Three enabling technologies were outlined, and some real-world measurements presented in this thesis.

First proposed enabling technology supports IPS stability during high renewable penetration by enabling standby diesel generators to rapidly synchronise during periods of high renewable energy generation intermittency. The technology is dubbed predictive synchroniser as it uses neural networks to predict future IPS frequency and rapidly place frequency and phase of incoming diesel generators in synch with the power system. By doing so, it decreases the chance of generation deficiency and increases IPS reliability of supply.

Second proposed enabling technology is fast-acting aggregated demand response which helps IPSs to have longer periods of diesel-off operation. By actively monitoring the controlled loads and controlling them in sub-second time periods, this enabling technology can rapidly reduce power system load during short-time lulls in renewable energy generation production and by doing so, maintain IPS stability and reduce cost of generation by prolonging diesel-off operation. Measurements taken in a real-world IPS support the proposed effectiveness of this enabling technology.

Finally, third proposed enabling technology is a synergy between synchronous condenser and a fast-acting battery energy storage. The proposed enabling technology supports IPS operating in diesel-off regime by providing power system inertia, sufficient levels of fault currents and rapid emissions-free real power support. Measurements taken in a real-world IPS support the proposed effectiveness of this enabling technology.

Overall, the work contained in this thesis has proposed and demonstrated three enabling technologies which further advance the integration of renewable energies in isolated power systems. Taken altogether, this thesis provides novel information, and represents a significant advancement to the operation on isolated power systems under high renewable energy penetration levels.

Dedication

This thesis is dedicated to my wife Sonja and our daughter Iva, for their love and enduring support.

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Chapter 1. Introduction

Parts of this thesis chapter have been previously published [10] in Author's consulting work for the Government of Republic of Marshall Islands:

Nicole Baker, **Dusan Nikolic**, Josh Curd, Andrew Revfeim, Will Thorp, Rob Solomon, Frank McLaughlin, Pat Hyland, "Navigating our Energy Future: Marshall Islands Electricity Roadmap," Republic of the Marshall Islands Energy Future, December 2018.

In addition, parts of this thesis chapter were previously published in:

Z. Nikolic, V. M. Shiljkut, **D. Nikolic**, "Diesel-solar electricity supply for remote monasteries", Journal of Renewable Sustainable Energy 5, 041815 (2013), Special topic: Renewable Energy in South-Eastern Europe, http://dx.doi.org/10.1063/1.4813068

Chapter short summary:

This Chapter introduces the classification of modern isolated power systems and challenges they are facing. It also outlines a roadmap to achieving high renewable contribution levels and based on it, defines Aims of this Thesis.

1.1. Overview

Electricity consumers living in remote areas or on islands often cannot be supplied from conventional interconnected power systems. These consumers are usually serviced by a local electricity generation and distribution system which are referred to as an ‘isolated power system’ (IPS). Electricity in IPSs is traditionally generated by diesel generators which consume diesel fuel. Remoteness, and the consequent high cost of diesel fuel supply, results in the cost of electric energy in IPSs being high compared to conventional interconnected systems. In some locations, the price exceeds US $1/kWh which is an obvious incentive for introducing renewable energy (RE) generation.

Unfortunately, RE from the two most abundant energy sources – wind and solar – is intermittent and incurs significant stability and reliability issues. A remedy for instability caused by RE was found in various technologies known as ‘enabling technologies’, as they enabled power system to operate stably during times of high RE penetration. Enabling technologies are usually not producing energy, they are either enabling an IPS to operate at a higher RE penetration level or increasing stability of the system without increasing RE penetration.

It is easy to deduce that the enabling technologies represent an additional capital cost since power systems normally do not charge their customers for energy stability, but only for delivered energy. The higher the penetration of RE in an IPS, higher amount of enabling technologies is needed, and higher the capital cost. Because of this increased cost, it becomes economically unviable to progress beyond certain level of RE penetration. In some IPS, this level could be as low as 50% [11].

The purpose of research in this thesis is to find less expensive alternatives to existing enabling technologies, propose new combinations of enabling technologies and optimise operation of enabling technologies, all of which would yield to more cost-effective operation of IPS, and consequently, higher RE penetration.

1.2. Background

1.2.1. Definition of Isolated Power Systems

Various names have been used to refer to the category of remote power systems including 'stand-alone power system', 'isolated power system', 'remote area power system', 'isolated grid', 'off-the-grid', 'mini-grid' and ‘micro-grid’. This thesis uses the term 'isolated power system' (IPS) to refer to any electricity network that satisfies the sub-GW, sub-100 kV criteria.

IPSs traditionally generate electric energy using diesel generators which consume diesel fuel. This is true for all sizes of IPS, from a small community of several house, to large island nations or mining operations.

1.2.2. Significance of Isolated Power Systems

As of 2017, there is about 7 billion humans on the planet. The world's population can be divided into three broad categories of electricity consumer according to their power grid connection:

a) *Connected to a traditional power system* - in industrialised parts of the world most electricity consumers are connected to a utility operated GW scale grid which has a HV (above 100 kV) power transmission backbone and may also have interconnectors to other similar scale networks.
b) *Not connected at all* - about 20% of humanity [12] lives without access to electric energy. When, in the future, this group gets connected to a power system, due to high costs of interconnected power system infrastructure, it is likely that a large number of people from this group will be connected to a future IPS, rather than interconnected power system.
c) *Connected to an IPS* – people not conforming to first two categories are a part of an IPS.

With the declining costs of small RE generation (predominantly residential solar PV), and energy storage technologies, many communities [13-16] which are connected to an interconnected power system are thinking of establishing micro-grids, which are capable of short or even long-term operation without the support of the interconnected power system.

Whether it is for providing electric energy for remote communities or enabling micro-grids to operate independently from the interconnected power systems, technologies and methodologies developed through the IPS research will continue to benefit a large proportion of the humanity.

1.2.3. Challenges in Isolated Power Systems

While interconnected power systems have a lot in common, IPSs exhibit a very wide range of operational, economic and electrical characteristics. Following are some of the challenges, in order of their significance to IPS utilities:

Cost of primary energy

IPSs generally do not participate in a wholesale electricity market, and often receives some kind of subsidy to protect consumers from higher operational costs. As IPS use diesel fuel, cost of energy largely depends on the price of diesel fuel. In the recent decades, this cost was not favourable for IPS communities, as shown in Figure 1.1.

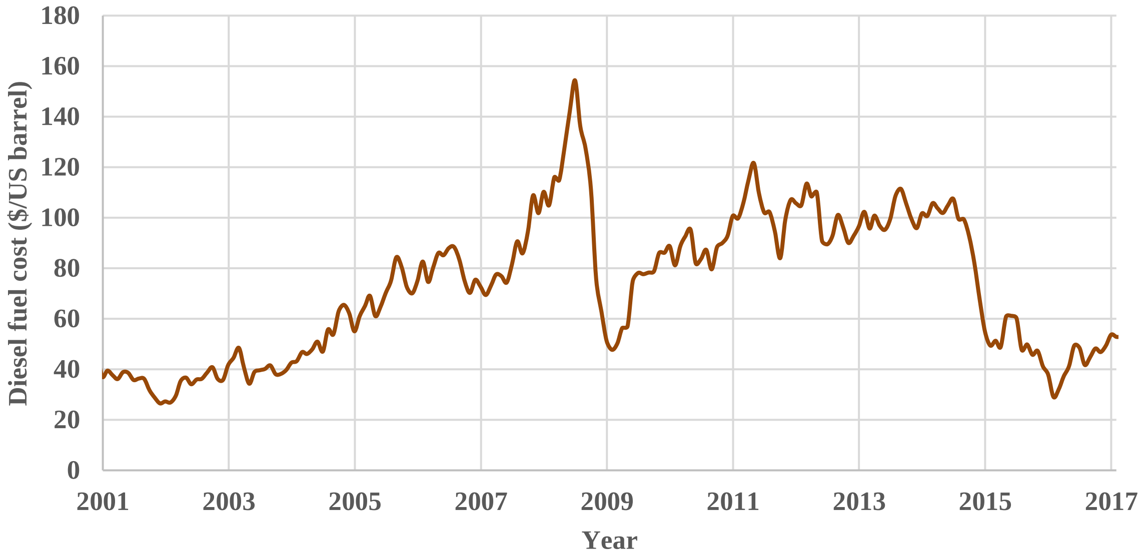

Figure 1.1 Historical cost of diesel fuel, per US barrel (West Texas Intermediate) [17].

Cost of fuel represents the largest component of an IPS operational cost, and any volatility of diesel fuel price directly reflect cost of energy in an IPS. Some Pacific nations are using a significant share of their GDP, between 3% and 23% [18], for fossil fuel imports.

With high diesel fuel prices, their volatility, and uncertainty of its future movements, it is no wonder IPSs are moving towards accepting RE.

Energy independence

As an example, all Island nations depend on IPSs for electric energy supply. Most of them, if not all, do not have any oil resources and depend on foreign imports to provide this essential resource for their economies. Sufficive to say that this arrangement puts all of those nations in a politically and economically dependent position towards larger nations. Similar energy dependence applies for non-island nation IPSs as well.

Energy quality

An IPS almost always delivers a lower quality service both in terms of SAIDI and SAIFI scores [19], and in terms of frequency and voltage stability. The reasons behind this are twofold: IPSs usually do not host high-technology or similar industries which require high electric energy quality, and they are using simple generation technologies, with little or no redundancy.

Knowledge capacity

An IPS is usually a traditional vertically integrated operation with as few as zero full time staff. It is no wonder these small utilities, operating simple technologies far from modern technology advances, host very little, if any, highly trained and capable staff.

While this IPS challenge is not immediately obvious, it can be explained through increased cost. Unskilled workforce does not maintain equipment properly, leading to frequent faults, and decreased equipment service life. Unskilled workforce does operate IPS efficiently, leading to missed opportunity in increased effectiveness in production and distribution of electric energy. This is mostly evident when new technologies are added to the system, and their maloperation leads to non-realisation of promised economic and environmental benefits.

1.3. Problem Statement – Progression to high renewable energy contribution in Isolated Power Systems

More than any other challenge, cost of diesel fuel in 2008 – 2009 [17] prompted IPSs to start implementing RE technologies, with a goal of reaching very high levels of RE contribution, and phasing out diesel generation altogether. Increasing renewable energy in the power system generation mix was met with two main challenges – decreasing power system stability, and unintuitively, rising cost of energy.

As an example, Pacific countries adopted a goal of 100% or near-100% RE contribution [20], with target dates ranging from 2020 to 2050. From their example, the implementation of high RE contribution in IPS can be perceived as a multi-phase process. It takes several projects and a certain amount of time for an IPS to reach near-100% RE operation. This is the reason why most IPSs refer to this transformation process to as a 'journey' rather than a discrete effort.

Length of RE journey and the effort required depends on the size and complexity of an IPS [11]. For IPSs of one mega-watt scale and larger, there are five distinct stages [10] on a journey to near-100% RE contribution:

1) *Near-0% RE contribution* – a starting point for many IPSs, who are exclusively supplied by diesel fuel. Figure 1.2 shows a daily load diagram for a typical isolated power system. Power system load (presented as a black line) varies during a day and experiences typical morning and evening peaks. At all times during the day, entire load is met by diesel generators, and all necessary power system services are provided by diesels. There is enough diesel generation capacity to cover entire power system load, and the load itself is above allowed minimal loading of diesel generators, which typically ranges between 10-30% [21, 22].

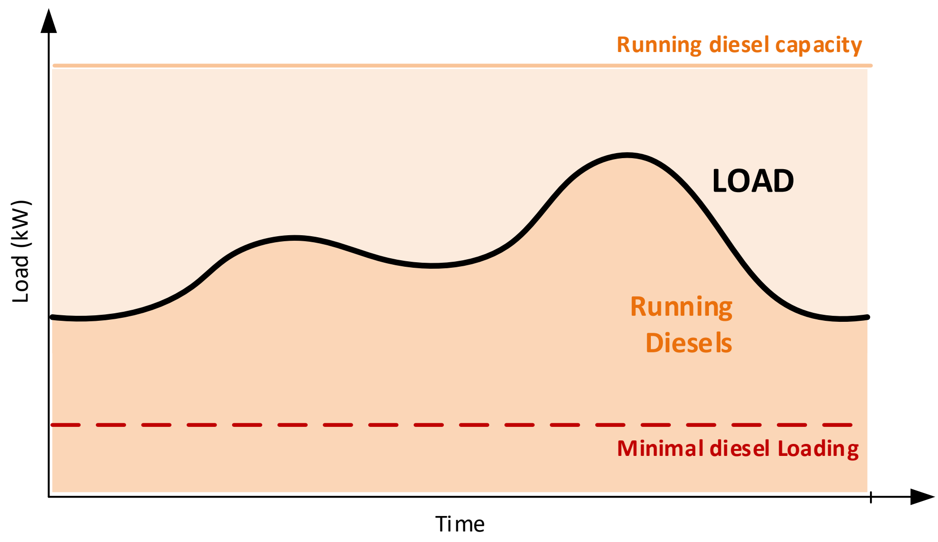

Figure 1.2 An example of 0% renewable energy contribution system daily load and generation diagram.

Some very limited renewable generation might be present in the system at this time, but its effect would be very small, and with an insignificant influence.

2) *Introduction of RE* – RE are installed to the point where they bear some, but no major influence on the existing diesel generation (Figure 1.3). At this point, RE are not actively controlled and are perceived mostly as a load offset. Diesel generation still has a full control over system frequency and voltage. As in previous stage, there is enough diesel generation capacity to cover entire power system load (meaning there is sufficient spinning reserve in spinning diesel generators), and the load itself is above allowed minimal loading of diesel generators. As renewable energy generation capacity grows, it will continue to lower diesel generator loading during times of high renewable penetration. With increased RE generation, minimal diesel loading becomes an inhibitor to further RE contribution.

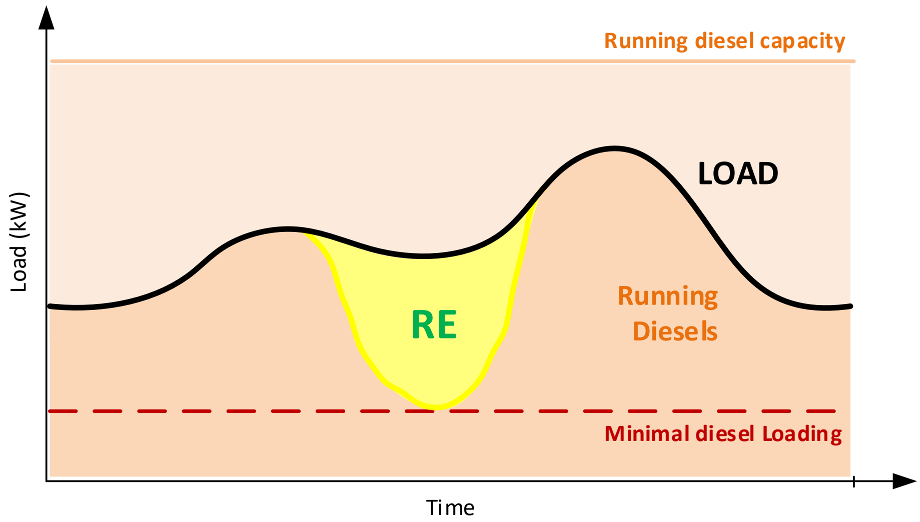

Figure 1.3 An example of low renewable energy contribution system daily load and generation diagram; solar generation is presented as an example where renewable generation reduces diesel generation loading to its minimally allowed limit.

On one hand, taking some of thermal diesel generation off-line during times of high RE penetration would lower total minimal diesel loading (as less diesel generators contribute to minimal diesel loading) and allow further increase of RE contribution. On the other hand, removing synchronous generation from the power system would mean less power system stability, especially during high intermittency of RE generation. Lower stability is a result of having less synchronous machines in the system, which lowers the system inertia, reduces fault currents provisions and reduces spinning reserves.

3) *Expansion of RE and introduction of enabling technologies* – As a solution to the problem of higher RE contribution versus less thermal generation, enabling technologies are introduced into isolated power systems. Enabling technologies are technologies such as batteries, flywheels, and are added to ISP's specifically to strengthen critical power system

services, such as spinning reserve, fault currents and inertia, which are reduced by removing diesel generation. By adding enabling technologies, they replace power system services diesel generation originally provided *without* consuming any fossil fuels. During this stage, remaining diesel generation may still stay in control of system frequency and voltage, although it may not have sufficient running capacity to cover entire system load (Figure 1.4). This state of a power system is only possible if enabling technologies provide sufficient spinning reserve and other power system services, needed for stable operation of an IPS.

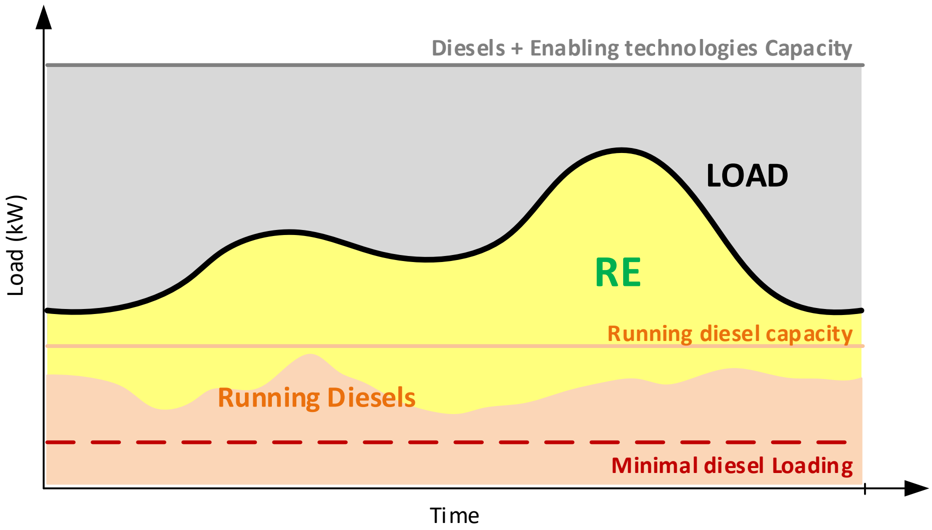

Figure 1.4 An example of medium renewable energy contribution system daily load and generation diagram. Diesel generation running capacity is not sufficient to cover entire system load by itself, which is why it is supplemented by enabling technologies.

4) *Further expansion of RE and enabling technologies* – Pursuing higher RE contribution requires higher amounts of RE generation and larger scale enabling technologies, which may allow it to run, for the first time, without diesel generators during favourable RE and system conditions (Figure 1.5).

During the periods of diesel off operation, RE sources provide power generation, while an IPS completely relies on enabling technologies for maintaining power system stability. All adverse power system events, from changing loads and system faults to managing RE generation intermittency need to be fully mitigated without diesel generators, using enabling technologies only. From an IPS customer point of view, system reliability must not change between diesel-only and diesel-off system operation.

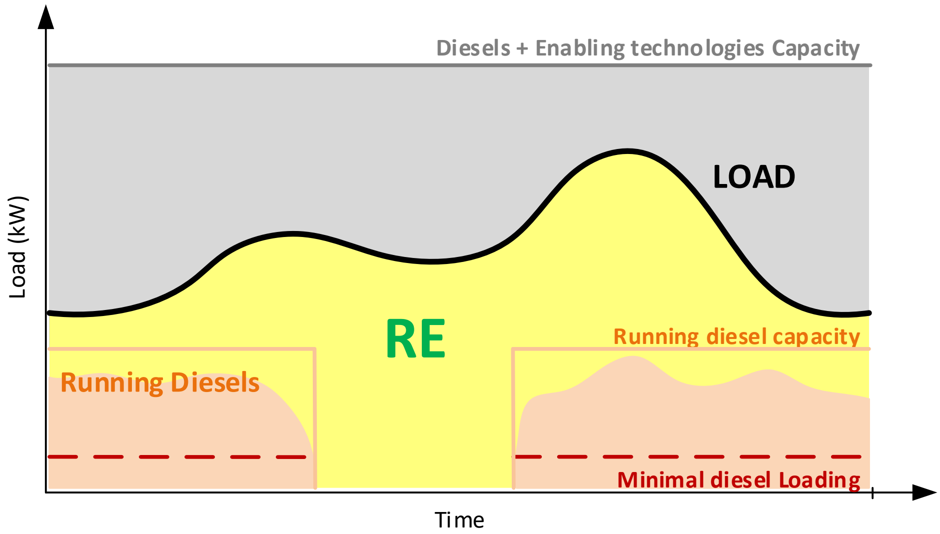

Figure 1.5 An example of high renewable energy contribution system daily load and generation diagram. During favourable RE generation and power system periods, ISP may operate without diesel generation for limited amounts of time (minutes, hours).

5) *Reaching near-100%* - when a sufficient amount of RE generation and enabling technologies is present in the system most of the time, an ISP can operate without diesel generators for extended periods of time (days, months). At this stage, diesel generators are almost never in control of system frequency and voltage and are present in the system mostly for emergency backup (Figure 1.6).

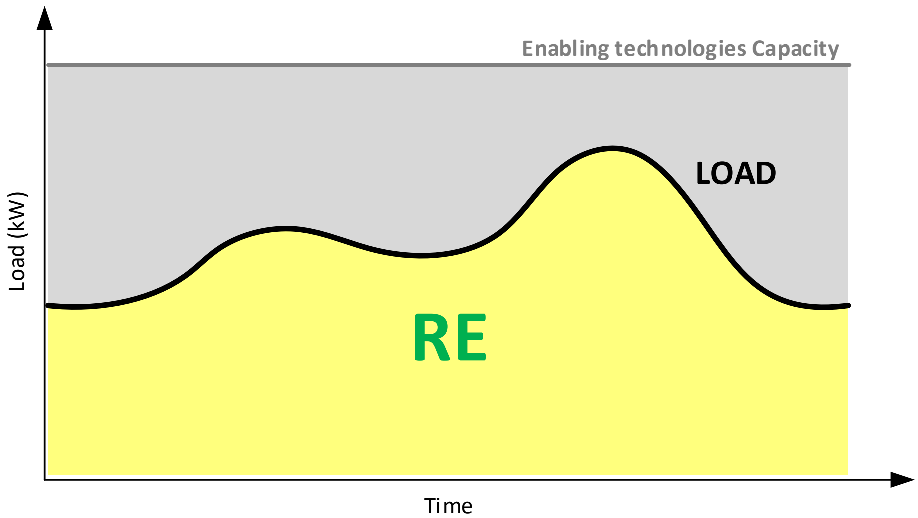

Figure 1.6 An example of fully renewable energy contribution system daily load and generation diagram. Diesel generation is either not present or present during faults as emergency backup generation.

As in previous stage, when diesel generators are not present in the system, RE generation produces all necessary energy for the system, while enabling technologies deliver power system stability by providing all necessary power system services such as inertia, fault currents, spinning reserve, etc.

As the RE contribution rises through five stages of RE journey, IPS operation cost related to consumption of diesel fuel decreases. On the other hand, the amount of infrastructure in IPS increases, due to new RE and enabling technologies, which in effect causes overall energy price to rise, as shown in Figure 1.7. Importantly, throughout the entire RE journey, a sufficient level of power system stability needs to be maintained.

Figure 1.7 shows an example from [11], where overall energy price decline as IPS starts integrating solar PV. As the IPS reaches about 50% of RE contribution, minimal cost of energy is reached. With further integration of RE generation, more enabling technologies are integrated as well, which results in overall cost of energy increase.

Interestingly, one of the main reasons for starting RE journey is reduction in cost of energy, while the example in Figure 1.7 demonstrated that energy cost may even rise above the initial levels as the IPS is approaching near-100% RE contribution. This increase is mainly because power system stability levels needs to be consistent throughout the RE journey, and enabling technologies are added to the system.

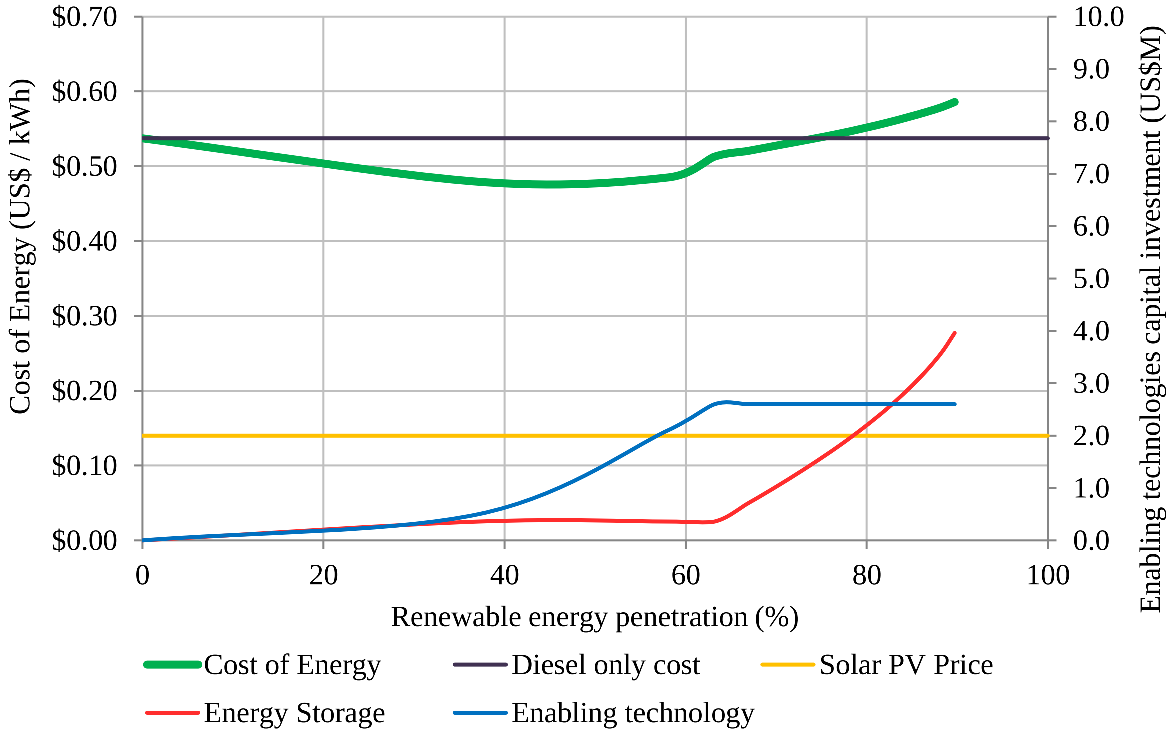

Figure 1.7 Example of cost of energy dependence on RE contribution [11]

In the wake of the Paris 2015 Agreement and with ever-rising prices of fossil fuel, finding appropriate techno-economic solutions for the progression of RE in ISPs will be of the vital interest of many ISP operators across the world, as well as nearly all Island Nations.

1.4. Thesis Aims

Two conclusions could be drawn from this Chapter:

1) A methodology needs to be developed which will help IPSs to select most effective and economically viable technology for reaching a desired level of RE contribution, and
2) For progressing further on the RE journey, and reaching higher RE contribution levels, it is necessary to develop enabling technologies which will provide sufficient level of power system services, cost-efficiently.

The overall goal of the Thesis is:

To develop lower-cost enabling technology alternatives which could fast track isolated power systems to higher renewable energy penetration levels.

Thesis will answer to the overall goal through three research aims:

1) Development of cost-effective technology for synchronisation of diesel generators in IPS during periods of high RE penetration and high RE generation intermittency,
2) Development of fast demand response for supporting high RE penetration by rapidly controlling part of the load and adding to power system spinning reserve, and
3) Development of enabling technology which provides sufficient level of power system inertia to high RE penetration IPSs and rapid real power support during lulls of RE generation.

Thesis aims are addressed in the following chapters.

0 reviews available and emergent enabling technologies which are suitable for use in IPSs. This chapter also serves as literature review for the thesis.

Chapter 3. responds to first research aim by introducing predictive synchronisation method as an alternative, cost-effective enabling technology. The purpose of the method described in this chapter is more effective synchronisation of diesel generation, which enables the system to endure higher RE penetration levels without costlier enabling technologies.

Chapter 4. introduces fast demand response as another alternative enabling technology. During levels of high RE penetration, instead of using costly battery energy storage enabling technologies, fast demand response can be used as a provider of spinning reserve in an IPS. This Chapter presents theory of operation of a fast-acting, sub-second, demand response, modelling, and operation results from a real-world IPS. This Chapter responds to the second research aim.

Chapter 5. introduces a methodology for determining inertia requirements for IPS during high RE penetration, which provides an IPS with the optimal stability versus cost of technology solution. As IPS progress to reach higher RE contribution levels, they tend to utilise diesel generation less, and substitute it with new technologies, which are predominantly based on inverter technology. Consequently, level of power system inertia in IPS declines, which influences IPS stability. This chapter also responds to the third research aim.

Chapter 2. Review of existing and emergent enabling technologies for increasing renewable energy in isolated power systems

Chapter short summary:

This chapter is a literature review of previous research efforts in the field of enabling technologies in power systems operating at high RE penetration levels. A common benchmark is established in the Chapter against which all enabling technologies are compared.

2.1. Introduction: The need for enabling technologies

IPS are usually powered by diesel generators which incorporate synchronous machines, and as such can provide electric energy and all power quality and power system stability services to an IPS:

1) Non-intermittent generation of real power (MW)
2) Non-intermittent generation of reactive power (MVAR)
3) Provision of frequency control
4) Provision of voltage control
5) Provision of fault level
6) Provision of system inertia
7) Provision of spinning reserve

RE technologies can generate real and reactive power primarily, but they fall short on providing most of other services. Lack of provision of all necessary services by RE leads to power system instability. These issues have been widely discussed in the research and industry literature [23-30].

A system compromising of only intermittent RE sources would not be able to provide power most of the time and provide necessary power system stability services to an IPS. To do that, an IPS would need technologies which are complementing RE generators, to provide all stability services that RE cannot provide. By doing so, those technologies would enable RE to operate in an IPS at very high RE penetration levels. Hence the name for those technologies, *enabling technologies*.

The following text in this Chapter will review currently available and emergent enabling technologies which have a potential to be used in IPSs. As the power system services listed in this section provide an excellent benchmark for understanding technical benefits and shortfalls of different enabling technologies, all enabling technologies will be benchmarked in a same manner.

2.2. New diesel generator technologies

Diesel generators consist of a diesel engine and a synchronous machine. Together, they can provide all necessary power system services for an IPS. It is no surprise then, that as a first step towards introduction of enabling technologies, some researches and industrial companies started with advancement in the existing diesel generators. Following sub-sections explore three of those technologies, biodiesel generators which use renewable fuels, low-load diesels which enable higher renewable penetration levels by operating at lower minimal loading levels, and diesel-UPS technology which enables diesel engine to de-couple from its alternator during high renewable energy availability.

2.2.1. Biodiesel generators

Biodiesel generators are similar to standard diesel generators, only using a different, renewable fuel source.

Biodiesel is commonly produced by the transesterification of the vegetable oil or animal fat feedstock. It can be gained from raw plant and animal-based materials such as coconut oil and soy, or from pre-processed materials such as used cooking oil and animal tallow. Biodiesel is used in biodiesel generators as mix of regular mineral diesel and pure biodiesel; most common used blends are B5 (5% pure biodiesel, 95% regular mineral diesel), B10 (10% pure biodiesel, 90% regular mineral diesel), B100 (100% pure biodiesel).

Since biodiesel generators are virtually the same as standard diesel generators, they can provide all power system services (as listed in 2.1.) to an IPS. In addition, well-established manufacturers and suppliers of biodiesel fuel exist, and biodiesel generators are readily available in the international market [31, 32]. If a fuel with high percentage of pure biodiesel is used, IPS could rapidly transform into a very high RE contribution IPS.

Communities which are paying high diesel fuel price but have high agricultural potential to grow plants suitable for biodiesel processing, could economically benefit from doing so. Authors of a paper [33] give an example is a community in Bangladesh, which started cultivating various edible and non-edible seeds to produce biodiesel. As a result, they have reduced their operating costs, limited exposure to volatility of diesel fuel price, and reduced environmental pollution. Pursue of lower operating costs and lower emissions has led [34] to present a comparative analysis of effects using diesel fuel oil, biodiesel and natural gas in hybrid solar, wind, battery, diesel generator IPSs. They have found biodiesel to be one of the best performers against the cost and emissions criteria.

There are however several shortfalls of biodiesel technology which have been tested and measured in recent industry projects [35]:

- The cost of biodiesel was found to be often slightly higher than cost of regular mineral diesel, since most of the time IPSs cannot cultivate and produce biodiesel but rely on importing.
- Depending on the climate conditions and fuel used, some biodiesel storage tanks need to be heated to prevent biodiesel (especially biodiesel made from animal tallow) from solidifying.
- Biodiesel generators were found to be slightly less responsive than diesel generators run on regular mineral diesel fuel. They were also found to be slightly less fuel efficient.
- Over longer periods of time, biodiesel causes more maintenance to diesel engine than regular diesel fuel.
- Finally, if lower biodiesel percentage blends are used (B5, B10) instead of B100, RE contribution is again limited.

To conclude, while biodiesel generators are similar in conventional diesel generators, due to fuel specific constraints listed above they are more complex to operate, and costlier to maintain.

Both benefits and shortfalls of biodiesel technology exist, however biodiesel generators could highly contribute to IPSs, when used as a last-mile technology, where they help IPSs reach 100% RE contribution.

2.2.2. Low-Load diesel generators

Typical diesel generators have an operating range between 50 and 100% of their rated capacity, while certain types of diesel engines have an operating range as wide as 30 to 100% [22]. While the higher percentage represents diesel generator rated capacity, the lower threshold is called minimal diesel loading, and represents minimal load set point which is predetermined to ensure engine efficiency and preserve engine reliability.

As RE generation is typically seen by diesel generators as a negative load, the lower the minimal diesel loading, the higher the RE penetration in an IPS. Low-load diesel generators [21] are capable of operating at a loading as low as 0 - 10%, allowing RE generation to reach very high penetration.

Sudden increase in RE generation can rapidly reduce loading of a diesel engine and push it into motoring mode. If in motoring mode, diesel generator will trip, and destabilise an IPS. Because of its operation at low loadings, low-load diesel generator is a system of a diesel generator and a dump load, which is able to quickly consume any surplus of RE generation and prevent diesel generator from entering motoring mode.

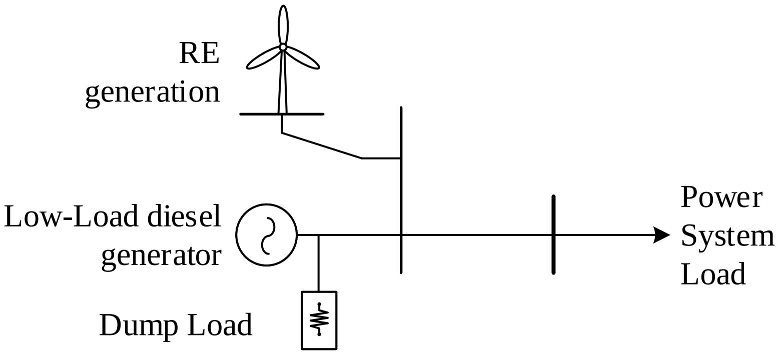

Figure 2.1 Low-load diesel - principle of operation

Operating diesel generators in low-load mode requires sophisticated controls, however it has been suggested [36, 37] that low-load diesel technology is mature enough to be reliably used in IPS. Their paper argues that the low-load technology reduces the complexity of the power system, as other enabling technologies become less necessary. Authors go further to claim that a low-load diesel generator technology can reduce the need for energy storage systems in IPSs.

Benefits of low-load diesel technology are reduction of diesel fuel use through increase of RE contribution. Low-load diesel generators are synchronous machines, capable of operating similar to standard diesel generators, and as such, capable of providing all power system services listed in Section 2.1.

On the other hand, low-load diesel generators are machines with higher complexity than regular diesel generators. Although they incur lower operating cost due to lower diesel fuel consumption, their fuel efficiency is poor, and they need to be serviced more often, which in return increases operating costs. Operating at low loads introduces more wear and tear to the diesel engine, therefore low-load diesel generators also incur higher capital costs as they need to be replaced more often than standard diesel generators. Finally, low-load diesel generators are more complex than standard diesel generators, thus harder to operate and maintain.

2.2.3. Diesel-UPS

Diesel-UPS system are used in load centres with a need for very reliable electric energy supply, such as hospitals, airports and sports stadiums. This technology is industry-proven and few manufacturers and suppliers exist on the market [38, 39].

Diesel-UPS has similar principles of operation to standard diesel generator. It uses diesel engine to propel an alternator, which generates electric energy. The main difference between the two is a mechanical clutch, which allows Diesel-UPS diesel engine to separate from the alternator and shut down.

Diesel UPS will start as a standard diesel and synchronise to the grid. Shortly after, mechanical clutch opens and diesel engine component shuts down. Alternator stays connected to the grid and provides voltage and system inertia support. Some types of Diesel UPS are equipped with a flywheel which is permanently connected to the alternator, for additional inertia support. In a case of adverse power system conditions, kinetic energy stored in alternator and flywheel can provide necessary real and reactive power to the grid for a short time, until diesel engine is started and coupled with alternator. Since the synchronisation of diesel engine to the alternator is mechanical (through a clutch) and not electrical, engine start-up and synchronisation process is very short and usually lasts a couple of seconds [38]. With its engine coupled and operating, Diesel-UPS can generate power for several hours, until grid power supply is restored, or standard diesel engine is synchronised and starts generating.

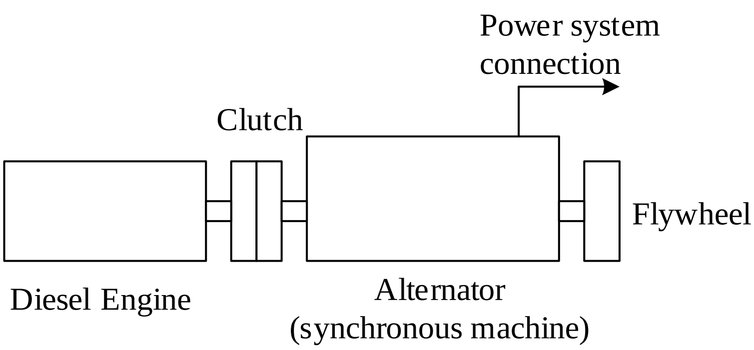

Figure 2.2 Diesel UPS principle of operation

It is interesting to note that the positive effects of Diesel-UPS technology as minimisation of cost related to power losses were realised early on. Back in 1987, Dolezal [40] argued that Diesel-UPS systems are perfectly suited for computer systems requiring high quality of electric energy. The author went on to mention that such a technology is advantageous to battery-based

UPS because it requires far less space, provides better quality of power supply and compared to battery systems, has a potential for longer power supply. Some authors [41] suggest using induction machines instead of synchronous, and DC/AC converter for start-up of diesel engine, as an alternative to battery-started, synchronous machine Diesel-UPS system. According to authors, this approach further decreases costs in running a Diesel-UPS system while providing reliable power supply.

Diesel-UPS technology was developed to provide critical power supply to important loads connected to traditional power systems. In recent years, these systems have found an application in IPSs [35].

As RE penetration rises in an IPS, its inertia starts can drop. When operating at high RE penetration levels, RE generators would provide most of the real and reactive power needed by an IPS. At the same time, IPS operators might choose to switch off some of the diesel generators, and to enable even higher RE penetration levels. As RE sources (such as solar PV and wind turbines) inherently have lower inertia that diesel generators, IPS as a whole would experience a drop in inertia, and consequently, higher frequency deviations due to RE intermittency [29]. A role for Diesel-UPS in such a system would be to stabilise the system by providing its inertia and fast diesel engine backup. In a case of sudden drop in RE generation, Diesel-UPS inertia could support the system for a couple of seconds until its engine is started and synchronised. In the next few minutes, conventional IPS diesel generators could be brought back on-line, and Diesel-UPS disconnected. A benefit of a Diesel UPS is that IPS could operate at very high RE penetration levels, and that any adverse system conditions very successfully mitigated, without loss of power supply to customers. Operation of Diesel-UPS in IPS was extensively trialled and tested in industry projects [35].

Since they are very similar in their operation to standard diesel generators, Diesel-UPS can provide all power system services (as listed in 2.1.).

While being very helpful in providing critical power system support, Diesel-UPS have several shortfalls:

- They cost significantly more than standard diesel engines, are harder to install and maintain,
- Diesel-UPS are complex systems, with few suppliers with limited support in all world regions,

- Diesel-UPS consume diesel fuel during the start-up and system backup time,
- While operating in a system, alternator (and flywheel) rotate at a synchronous, system speed. Their operating losses are supplied by the power from the grid, which means that their constant operation incurs constant parasitic losses to a system, and
- They usually require sophisticated control systems for their proper integration into high RE penetration IPSs.

2.3. Dump Loads

2.3.1. Simple Dump load

Dump load is an established enabling technology which has been present in power systems for a number of decades, and was a focus of a number of researchers [42-53]. The role of dump loads in IPS is straightforward; any sudden surplus of power produced by RE generators can be absorbed by dump loads. If an energy storage technology exists in an IPS, dump load is used to dissipate surplus of available RE power when the energy storage is full.

Traditional role of a dump load was described by several authors [47, 48, 50, 53] where they proposed using dump load as a consumer of surplus RE power. In addition to its traditional role, Wang et al [43] proposed using dump load as a way to protect small wind turbines without pitch control from overspeed in high wind speed situations. Authors go on to propose dump load to be effectively used as a brake when a wind turbine is disconnected from a system. Other researchers [44, 45] see dump load as a way to optimise operation of an IPS. Optimisation of IPS operation by using dump loads can even lead to increased RE generation as explained by Arriaga in [51]. Dump load was also proposed by researchers as a supporting frequency control unit in IPSs [46, 52].

Dump load technology is nowadays well-established technology, well covered by researchers, and it is worth summarising this technology's benefits and shortfalls.

Dump load is a very simple technology, with a small capital cost, and very little required maintenance. It usually has a very simple control system, if any at all and is highly controllable. It is a very compact, highly reliable technology. As explained in this section, dump load can be used as an enabling technology for consumption of excess power in an IPS. Instead of limiting RE generation output, excess power can be dissipated in a dump load. Load that is consumed by a dump load can be quickly absorbed or rejected, providing an IPS with immediate spinning reserve.

On the other hand, dump load is an enabling technology which only consumes power and is not storing it. It usually produces a large amount of heat which needs to be ventilated from a power station, or the whole dump load unit needs to be installed outside the power house, where it is exposed to elements. Of all power system services described in 2.1. , dump load is only capable of producing spinning reserve.

2.3.2. Frequency controlling Dump load

Frequency can be controlled by a dump load when it is being used to dissipate RE energy surplus. A frequency controlling dump load is a special type of dump load technology, capable of rapidly changing its resistance, and hence power. By doing so, it contributes to balance between generation and load and assists in frequency control.

Crude dump load frequency control can be achieved by controlling a dump load which has a large number of stages (Figure 2.3.a), or individual resistors which are switched on and off. The more stages a dump load has, more fine-grained frequency control is. For IPSs which do not have strict frequency requirements, this dump load with discrete stages is a sufficient enabling technology. This technology was used [52] to supplement battery energy storage in fine frequency control.

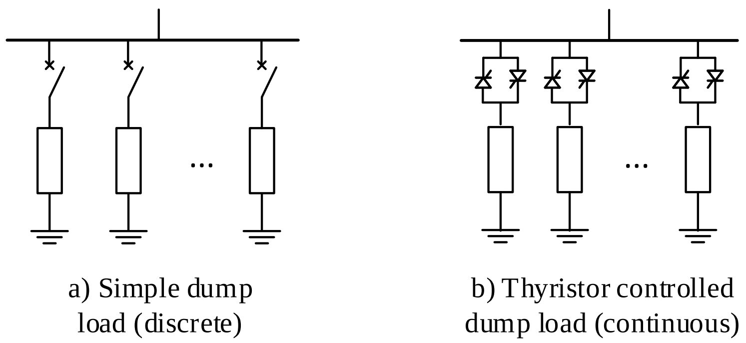

Figure 2.3 Two types of frequency controlling dump load

Figure 2.3.b shows a simplified schematic of a thyristor-controlled dump load which provides fine frequency control. Due to its thyristor control, it can consume any power between 0 and 100% of its rated capacity and it can smooth out any intermittency coming from RE generation.

This technology is proven in industry projects [35], and it demonstrated that is capable to take over frequency control from diesel generation.

Frequency controlling dump load has similar benefits to simple dump load, with the addition of frequency control to the list of power system services listed in Section 2.1.

Frequency controlling dump load also has similar shortfalls to simple dump load. In addition, this enabling technology is more complex than simple dump load.

2.3.3. Demand Control

Using controllable demand (mostly industry non-critical loads) during adverse power systems conditions is an established practice in traditional, interconnected power systems.

Recently, with the proliferation of RE generation, controllable demand has found a new use in enabling higher RE penetration in power systems, and since then, becme a hot topic in research circles. This chapter lists relevant research under the Thesis topic.

Instead of using large industrial loads, aggregation of a vast number of residential loads was proposed [54] and which would act as a link between the customers and the market. By doing so, authors have managed to match surplus of renewable generation, satisfy network constraints leading to benefits from reduced use of peaking plant and avoided network reinforcement. Others [55] proposed forecasting RE generation (wind and solar), and using demand response as a RE prediction error mitigation technique. Their findings report successful operation of the system without surplus thermal generation. Both mentioned papers focus on demand response matching renewable generation.

Some researchers [56] have moved a step further to propose using demand response as a spinning reserve in the Danish interconnected system which experiences large wind penetration. Similar research [57] introduces an even fine-grained concept by suggesting demand control of individual domestic appliances. Both studies reported that use of demand response enabled higher RE penetration and postponed start-up of thermal generation.

Following success of demand response in interconnected systems, researchers started looking at its application in IPSs. Some [58] developed and successfully tested a mathematical model for combined use of demand response and energy storage for lower curtailment of RE in IPSs.

Application example of demand response in [3] used fast, sub-second demand response to postpone diesel generation start-up in weak IPSs.

Research theories were later proven in practice in IPSs. Rottnest Island (Perth, Australia) [59] uses its desalination plant as a controllable load during periods of excess RE generation, and its water tanks as virtual energy storage. By doing so, it was capable to reach up to 60% RE contribution without using any battery energy storage. Distributed, residential and commercial demand response is used on Kind Island (Tasmania, Australia) [35] to control distributed and aggregated island loads during high RE generation. prolong 100% RE operation on the island.

Chapter 4. describes operating principles and results of a fast demand response system, capable of prolonging 100% RE operation on the island by quickly reducing overall island load during short-term RE generation lulls.

Although some authors have suggested using demand response for frequency control, IPSs are usually weak low-inertia systems, with rapidly changing frequency. This is why demand response application in IPS is mostly limited to provision of spinning reserve only.

If favourable (easy to integrate, available, dispatchable and relatively local) demand response exists in the system, it could be easier to integrate, control, and cheaper to install than various energy storage technologies. Shortfalls of demand response are that is almost always depends on fast and reliable communication pathways, it is not always applicable, or economically favourable, it needs sophisticated control system, and it performs direct operation of customer loads.

2.4. Synchronous condensers

Synchronous condensers (SCs) are another well-established technology which existed in power system for several decades. SCs are typically used for local voltage control, reactive power provision, and addition of inertia into the system [60-62]. In the last few decades, use of SCs was on the rise due to increased integration of RE generation into power systems, and most of all, large wind farms.

Since SCs are basically synchronous machines without the prime mover, electrically connected to the grid, they provide all power system support services a synchronous machine would: voltage control and reactive power generation, fault currents and system inertia (if connected to the grid via a converter, their inertia and fault current provision could be very limited). In recent years, as a result of large increase of RE generation, SCs found new use in IPSs as well [63].

As RE penetration increases, so does the interest of researchers in SCs as an enabling technology. Research in [64] has described a role for a SC as an enabling technology supporting wind power plant connection to a weak grid. Other researchers [65] argue that SCs could support frequency control by contributing to system's inertia. One way or another, SCs are found to impeccably complement weak, low-inertia high RE penetration systems.

It is important to note two main types SCs, one where an SC connects to grid directly, and one where it connects to the grid using an inverter. The first type has the ability of providing system inertia and fault currents, while the second one has more sophisticated voltage and reactive power controls.

Due to their simplicity, SCs are a relatively low-cost, yet reliable enabling technology. They are easy to maintain and incur low operation and maintenance costs during their service life. One of the main shortfalls of a directly-connected SC is that it uses real power from the grid to cover its operational losses [35]. A control system is then necessary to determine when an SC is needed in the power system, if system losses are to be optimised. If connected to the grid via an inverter, an SC has very limited ability to provide fault currents or system inertia.

Typical cost of an SCs depends on its size; a 1 MVAR could be procured and installed for a price of $0.3 US per watt [63]. Because of their benefits, it is easy to see that SCs will play a role in high RE penetration IPSs.

Chapter 5. discusses a novel technology which utilises synchronous condenser technology directly connected to the grid and supported by an inverter-led battery energy storage system. This technology would provide all necessary power system services through its SC, while short-term battery energy storage would emulate behaviour of a diesel engine for a short period of time, supporting the system until other conventional generation is brought online.

2.5. IPS Control systems

IPSs on the journey to high RE penetration require several new technologies. Diesel generators are still present to support the system during times of low RE generation availability, then various RE generators are present in the system and supporting them, additional enabling technologies. As an IPS is transiting through periods of high and low RE penetration, its configuration can drastically change, whilst it must maintain its energy quality and reliability of service. Control systems are another enabling technology which is used for scheduling of various technologies in an IPS.

An example of a simple controller enabling technology is described in Chapter 3. This ‘predictive synchroniser’ controller technology supports high RE penetration by allowing diesel generators to rapidly synchronise to an IPS during lulls of RE generation.

When a high RE penetration level is reached in IPS, a more complex, system-wide control system must be present to ensure active control of RE generators and maintain power system reliability. Its roles have been thoroughly summarised in [66].

Control systems are normally used in IPS as generation scheduling tools for achieving optimal operation in view of reliability or minimised operation cost and emissions. Some researchers [67] suggest a centralised control system which maximised RE penetration and minimises operational cost in an IPS. With increased number of new technologies in IPSs, control systems became complex; as a solution, others [68] proposed a three-tiered approach to control systems which controls individual generation, overall IPSs generation and in case of grid-connected systems, its interaction with the grid. Further research on the topic [69] follows multi-layer approach shown in [68] and further introduces a control system with centralised and decentralised control on individual layers. As the IPSs progress in their complexity, the significance of control systems rises, as can be witnessed by the published amount of research on this topic.

Control systems are widely present and are being used in industry projects by reputable, world-known companies. ComAp company offers entry-level controllers [70] for IPSs featuring diesel generators and solar PV or wind RE generation. ABB company offers its solution for integration of diesel and RE generation using flywheel storage. Hydro Tasmania’s proprietary control system [35] is technology agnostic and capable of integrating any enabling technologies into a high RE penetration IPS.

2.6. Energy storage

2.6.1. Inverters

Inverters are a technology used for conversion of DC electric energy into AC, and are used as a part of battery energy storage systems in IPSs across the world [71, 72]. Recent advancements in semiconductor technologies allowed inverter technologies to become very useful in IPSs, as they can provide a number of services needed by those systems.

Modern inverters can provide active and reactive power in full four-quadrant regime, allowing it to import or export both active and reactive power at its rated capacity, and assume a range of states in between. By doing so, inverters are far more flexible than traditional generators. Inverters used in IPSs can also provide frequency and voltage control and even support power system inertia by emulating its inertial response.

Downsides to this technology is its inability to provide real power system inertia, and its limitations in terms of fault current provision, which remains very low compared to synchronous machines.

Due to their flexibility and ability to pair with batteries (chemical energy storage) inverters are one technology which have already found their way into the IPSs and will most probably remain to be an important part of those systems.

2.6.2. Chemical batteries

Chemical batteries, or short, batteries are centuries old technology which store energy as chemical energy and convert it into DC voltage and current at its terminals. Batteries are well understood and convenient technology, which already has its place in IPSs around the world [71, 72] and is present in every aspect of modern life. With recent advances in battery technologies [73], and promise of future abilities, it is very likely this technology will be integral in high renewable energy penetration IPSs.

Two types of batteries should be mentioned here as they perform different roles in IPSs:

- High-discharge capacity batteries (‘performance batteries’) capable of discharging their entire stored energy in less than one hour. These batteries are useful in IPSs as a cost-effective short-term energy storage which enables high renewable penetration by allowing time between drop of RE generation and start-up of standby diesel generation.

- Low-discharge capacity batteries capable of discharging their entire stored energy in timeframes higher than few hours. These batteries are used in IPSs for storing larger amount of RE for later production (energy shifting).

Positive sides to battery technology are that it is well understood, it requires low maintenance, has very few or no moving parts, can be scaled to virtually any size, is proven to work in any environment, produces very little or no GHG emissions. There are different types of batteries which cater for specialised purposes, such as slow or rapid charges, long life or energy density.

Downsides to battery technology are its low energy density, cost, depth of discharge dependence on temperature and limitations on number of cycles and overall battery life.

2.6.3. Flywheels

Flywheels are the technology which are used in power systems to provide either power system inertia or act as a short-term energy storage, and by doing so, facilitate higher RE penetration in IPSs [74].

First type of the flywheel system uses flywheel mass as addition to the mass of the synchronous machine rotor [38]. By doing so, this type of flywheel system directly adds to the power system inertia, which is the primary advantage of this technology. Its major shortfalls are higher parasitic losses (incurred by air friction and increased synchronous machine bearings friction), as well as high amount of energy and time necessary to bring them up to nominal rotational speeds.

Second type of flywheels is used as short-term energy storage where energy is stored in the rotating mass of the flywheel, which spins at high rotational speeds. Extracting energy from the flywheel means slowing it down from its nominal to very low rotational speeds. This type of a flywheel is usually connected to a power system through an inverter which facilitates the conversion of rotational energy into electrical. Several large international engineering companies such as Caterpillar [75] and ABB [76] offer this type of flywheels. Positive sides to this technology are low parasitic losses (as flywheels are suspended in magnetic fields and vacuum) and somewhat similar behaviour to battery energy storage. Its major downside is that its inverter decouples it from the power system, so this technology does not contribute to real power system inertia nor is it capable of providing necessary fault currents, due to inverter limitations.

2.6.4. Hydrogen energy storage

Hydrogen energy storage was in focus of research in the last decade [77], and in particular, very popular with Japanese researchers [78-80]. One of the main reasons for researching hydrogen is its high energy density. As such, its' uses were found both in energy and transport sectors.

In IPSs, hydrogen is created using the process of electrolysis which separates hydrogen from the oxygen using electric energy. Hydrogen is then stored in usually pressurised tanks for later conversion into electric energy using fuel cells.

Hydrogen energy storage advantages are higher energy density than other energy storage technologies used in IPSs, and ability of almost indefinite storage without loss of the stored energy. Its major downside is round-trip efficiency which is lower than round-trip efficiency of traditional battery energy storage, making its' cost of energy less competitive.

2.6.5. Other energy storage technologies

Chemical batteries and flywheels are only some of the energy storage products available in markets. New technologies such as storing energy in a form of pressurised air, and then expanding it to retrieve energy promise to be cost competitive with chemical batteries. In warmer climates, thermal energy storage (molten salts) technologies were tested and proved to operate on larger scales. These technologies, and other new energy storage technologies have one thing in common – they were not trialled for decades in IPSs in different climates and under different conditions. As such, they do not form the 'energy storage mainstream' and are not considered in this Thesis.

Finally, a century old, proven energy storage technology is hydro or pumped hydro storage. While this technology offers all advantages of energy storage and all necessary power system services, it requires very specific geographical conditions, which are not common in IPSs. Some of the good examples of hydro generation being used in IPSs are in the islands of Viti Levu (Fiji), Pohnpei (Federated States of Marshall Islands), Upolu and Savai'i (Samoa), Reunion (French territory in southern Indian Ocean), El Hierro (Azores Islands). Nevertheless, vast majority of IPSs is not fortunate to enjoy this resource, which is the reason why hydro generation is not considered in this Thesis.

2.7. Summary of enabling technologies

All enabling technologies outlined in this Chapter were benchmarked against seven power quality and power system stability services to an IPS outlined in Section 2.1. and other technical, economic and environmental criteria. Table 2.1 summarises benchmarking results.

Table 2.1 Capabilities of different enabling technologies - summary

#		**Real power generation**	**Reactive power generation**	**Frequency Control**	**Voltage Control**	**Provision of fault currents**	**System inertia**	**Spinning Reserve**	**Capital cost**	**Operational cost**	**Complexity**	**GHG emissions**
1	Diesel generators	✓	✓	✓	✓	✓	✓	✓	Low	High	Low	High
2	Bio-diesel generators	✓	✓	✓	✓	✓	✓	✓	Low	High	High	High
3	Low-Load diesel generators	✓	✓	✓	✓	✓	✓	✓	High	High	High	High
4	Diesel-UPS	✓	✓	✓	✓	✓	✓	✓	High	Low	High	Low
5	Simple Dump load	✗	✗	✗	✗	✗	✗	✓	Low	Low	Low	N/A
6	Frequency controlling Dump load	✗	✗	✓	✗	✗	✗	✓	High	Low	High	N/A
7	Synchronous condensers	✗	✓	✗	✓	✓	✓	✗	Low	Low	Low	N/A
8	Control systems	✗	✗	✗	✗	✗	✗	✓	High	Low	High	N/A
9	Inverters	✓	✓	✓	✓	✗	✗	✓	High	Low	High	N/A
10	Chemical batteries	✓	✓	✗	✗	✗	✗	✓	High	Low	High	N/A

#		Real power generation	Reactive power generation	Frequency Control	Voltage Control	Provision of fault currents	System inertia	Spinning Reserve	Capital cost	Operational cost	Complexity	GHG emissions
11	Hydrogen storage	✓	✓	✓	✓	✗	✗	✓	High	High	High	N/A
12	Flywheel	✗	✗	✗	✗	✗	✗	✓	High	Low	High	N/A

2.8. Conclusion

Diesel generators traditionally provide electric energy and all necessary power system services to isolated power systems. No other single technology currently available on the market can provide the same level of service as diesel generators, which is why several enabling technologies are used in unison to support isolated power systems with high renewable energy penetration.

Different enabling technologies also have complementary characteristics, as shown in Table 2.1. This is true for dump load or demand control which are complementary with synchronous condensers. Similarly, chemical batteries connected to a power system through inverters are fully complementary to synchronous condensers, as together they can provide all power system services, which is explored later in this thesis.

Chapter 3. Cost-effective technology for diesel generator synchronisation under variable frequency conditions

This thesis chapter has been previously published [81] in entirety:

Michael Negnevitsky, **Dusan Nikolic**, Martin de Groot, "Adaptive Neuro-Fuzzy Synchronization in Isolated Power Systems with High Wind Penetration," Journal of Advanced Computational Intelligence and Intelligent Informatics, vol. 20, pp. 418-428, May 19 2016.

Chapter short summary:

This chapter presents the concept of the predictive synchronisation which can be utilised for faster diesel generator synchronisation into an isolated power system experiencing high frequency deviations due to high renewable energy penetration. Predictive synchroniser is a simple enabling technology, as it enhances existing infrastructure (diesel generators) and results in faster synchronisations, as consequently, enables power system to reliably operate at higher renewable energy penetration levels.

3.1. Synchronization Challenges in Isolated Power Systems

Isolated power systems (IPSs) worldwide are traditionally powered by diesel generators that are very expensive to run and produce harmful emissions. In order to mitigate these problems, wind turbines are being introduced into existing IPSs. Although this integration has been reasonably effective at reducing running costs and emissions, high levels of wind penetration cause large system frequency variations, resulting in a prolonged synchronization process for newly dispatched diesel generators. Long synchronization can compromise the stability of a small IPS. This chapter examines the diesel synchronization problem using a real IPS as a case study and offers a solution by introducing the concept of predictive synchronization based on adaptive neuro-fuzzy systems. Simulation results demonstrate a significant reduction in diesel generator synchronization times.

Previous research has focused on trying to solve the problem of high frequency variation by introducing new technologies which should help smooth the high RE variability, as presented in Chapter 2. While all researchers recognize the problem of high wind variations, they have largely ignored potential power system problems caused by those variations. The main reason cited for reducing frequency variation is usually the general need to improve power quality. As an alternative to solving the problem of high frequency fluctuations, this paper focuses on improving synchronization times during high frequency fluctuations in sub 10 megawatt scale, low-inertia wind-diesel IPSs with no energy storage. This chapter proposes a predictive synchronization method which can be implemented in a low-cost synchronizer. The proposed method is based on predicting the system frequency and phase two seconds ahead and adjusting the phase of the diesel generator in order to put it in a statistically better state for performing the synchronization. This chapter examines a very specific power engineering problem requiring short term forecasting and offers a solution using neural network prediction algorithms.

Diesel generators are used extensively in IPSs – they are proven technology. Control, governing and synchronizing equipment for these generators has usually been built for a completely diesel ‘genset’ supplied power system. Since IPSs are usually remote, their maintenance incurs higher costs. Therefore, IPS equipment needs to be sufficiently robust to reduce maintenance requirements. Hence, all components – including synchronizers – should operate on simple and well proven principles. A further consequence of this simplicity is the low cost of modern diesel system synchronizers (usually below US$1,000). Figure 3.1 shows daily diagram of operation of a typical IPS with virtually no renewable generation.

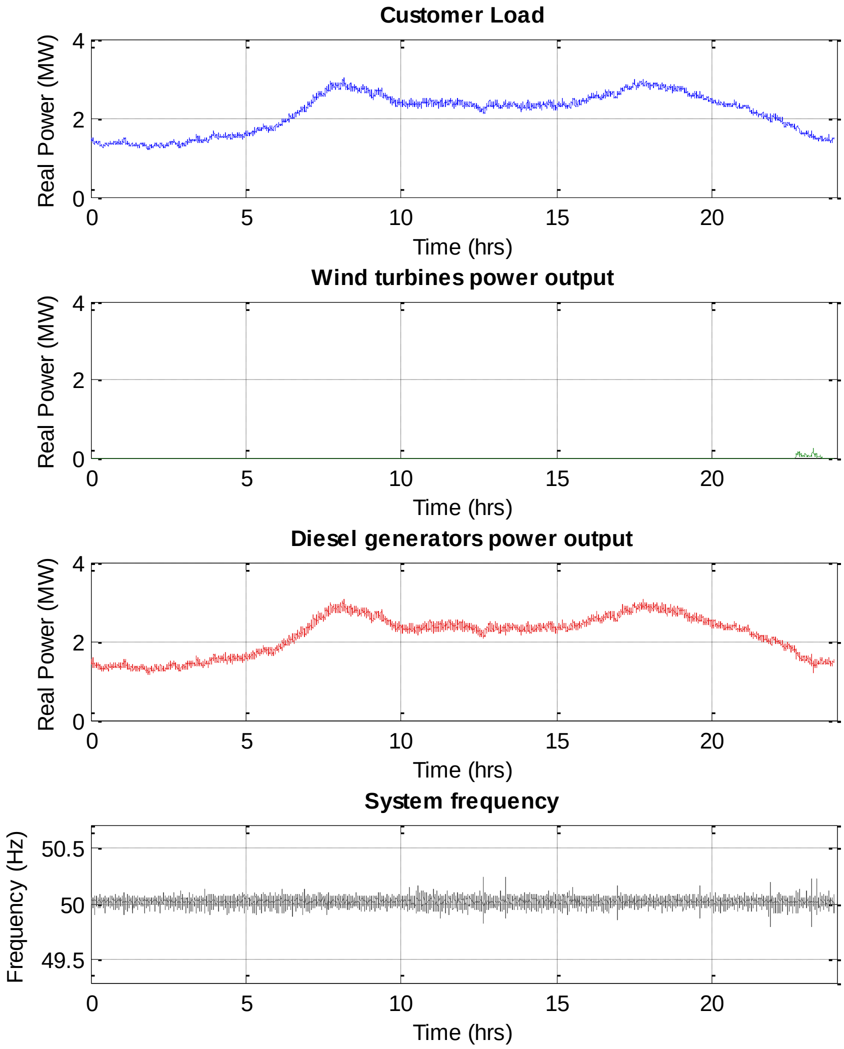

Figure 3.1. Profile of a typical daily load in a 3MW scale IPS. The load as seen by the diesel generation changes slowly during the day. Data for this example is taken from our case study system described in Section 3.3.

As the customer load changes slowly during the day, so does the diesel generation. This scenario results in a very stable system frequency that is almost steady at 50 Hz.

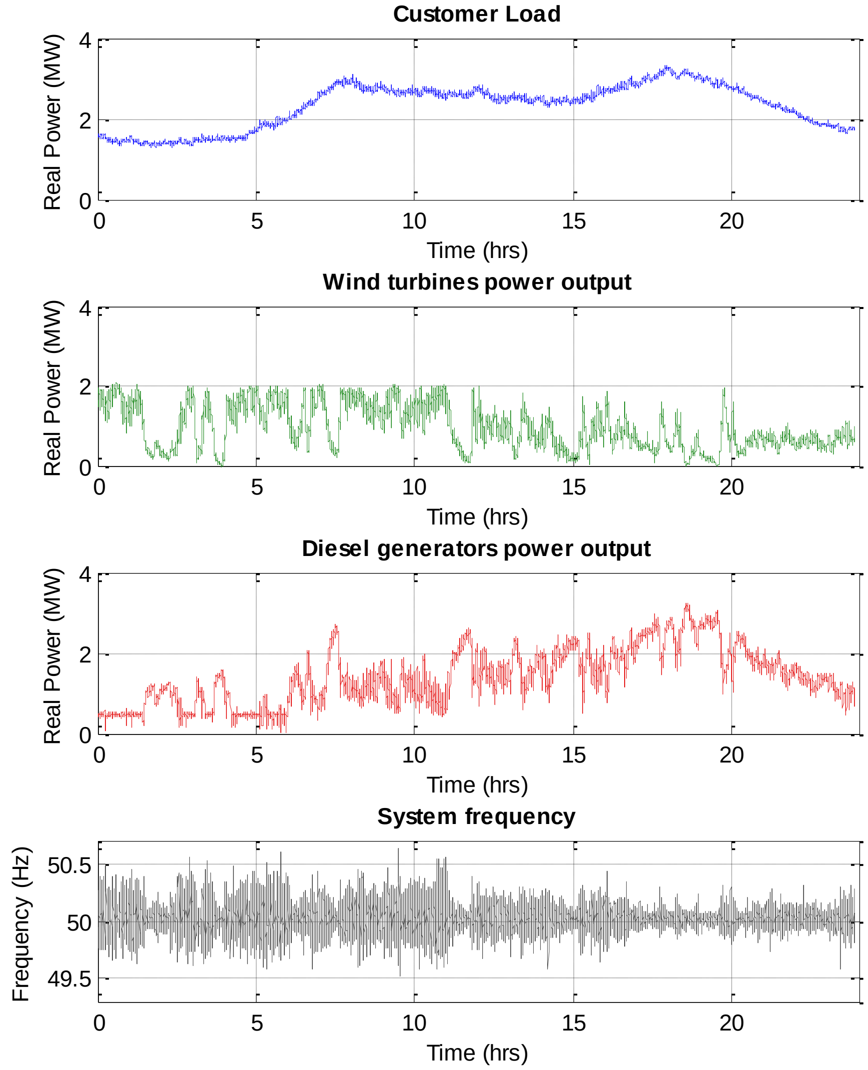

Figure 3.2 Daily load diagram in an IPS as seen by conventional diesel generators during high wind generation power output is highly variable and does not necessarily reflect the usual peaks or dips

In the past few decades, many IPSs around the world have started integrating RE in order to reduce operational costs. As a result, completely new hybrid systems with a range of generation sources and operational characteristics have emerged. In contrast to conventional grids, IPSs not only supply less power (usually MWs, not GWs) they are also spatially much smaller. Being smaller in capacity means that demand is less predictable. Being smaller in area means that supply from RE sources is more variable – as a larger percentage of the RE generators are likely to be affected by the same weather events (e.g. a lull in the wind or passing clouds). Due to their reduced demand predictability and the increased variability of RE supply, conventional generation scheduling in IPSs with RE is more challenging. From a generation scheduling perspective – where RE generation is usually treated as a load offset – the daily load curve becomes extremely volatile. An example load curve for an IPS with RE is given in Figure 3.2. Notice that diesel generation does not even have the usual morning and evening daily peaks.

High load variation makes scheduling of diesel generation more difficult and less efficient, as diesel engines will rarely operate at their peak efficiency, and more generator start-ups are required. As a result, synchronizing equipment built for the diesel-only IPSs is forced to work more often and in more difficult power system conditions. At the same time, because of the high variability of RE, diesel generation must be dispatched faster than in diesel only IPSs. Meeting these requirements is difficult for standard, diesel-only IPS synchronizers.

Standard Synchronisation Method

Synchronization process enables a generator to be connected to the power system. In technical terms, the goal of a synchronization process is to set the synchronizing generator to match the target power system frequency and phase. When two signals are sufficiently close to each other, a generator circuit breaker is permitted to close, and the generator is electrically connected to a power system.

Common analogue synchronizers perform the synchronization process in the way shown in Figure 3.3, which can be described as follows. As their inputs, synchronizers use the power system and generator phase to phase voltages. Based on the present generator and power system voltage phase, the synchronizer will calculate the speed correction signal it needs to send to the synchronizing generator. This signal is processed using the synchronizer's internal PI (proportional-integral) controller. After processing, the signal is sent to the diesel engine governor. Diesel engines have an inherent delay in responding to governing changes, which is usually around 250 ms. When the generator starts responding to a speed correction signal, it slowly ramps to a new value [82]. When a synchronizer sees that the generator and power system frequencies and phases are within allowable limits, it issues a close command to the circuit breaker (CB).

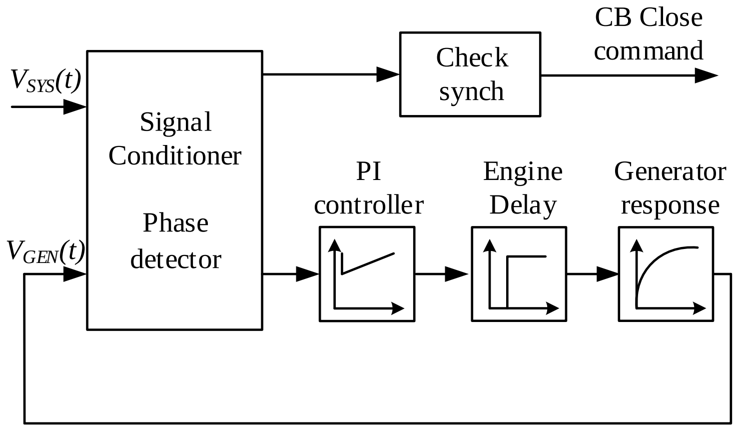

Figure 3.3. Functional diagram of a conventional synchronizer control loop [82]

An example of the synchronization process described above is presented in Figure 3.4. As can be seen, the conventional synchronizer was able to reduce phase and frequency differences between the synchronizing generator and the system within a relatively short period of time – the entire synchronization process took less than 7 seconds.

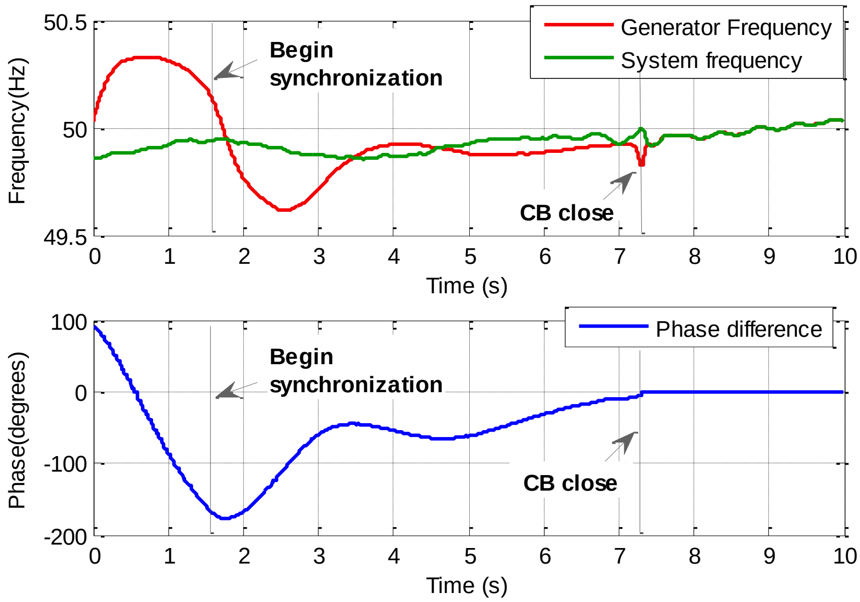

Figure 3.4. System frequency and synchronizing generator frequency during a conventional synchronization process. Data for this example was taken from the system used in the case study (described in section 3.3.) during a real synchronization event.

Most synchronizers operate according to principles similar to the method described in Figure 3.3. The two most common methods are known as ‘slip’ and ‘phase matching’ synchronization. Without explaining in detail each of these two methods, it is sufficient to note that both employ a PID control loop and vary only in the way that generator settings are calculated. Note that generators in conventional, large power systems have more sophisticated synchronizers with advanced control algorithms [83]. However, this sophistication comes at a cost (~ US $10,000) which is hard to justify in a small IPS.

Common Problems During Synchronization

Three most common synchronization problems in IPS are:

a) Out-of-phase synchronization. If the generator and system voltages are not exactly matched, but slightly shifted in phase, a voltage difference across the CB is created. This further creates generator inrush currents, which are potentially damaging to synchronous generator windings.
b) Out-of-frequency synchronization. Out-of-frequency synchronization happens if generator and system voltage signals have slightly different frequencies. When a CB closes, online generation and synchronizing generator experience power swings while trying to match speed. This is usually not a problem in conventional power systems, since the synchronizing generator will be pulled into synchronism by the overwhelmingly larger amount of online generation. In smaller systems, however, if only a small number of generators are online, the power swing can be significant. Power swings potentially create large currents and system frequency oscillations.
c) Prolonged synchronization. This condition arises if a generator fails to synchronize in an appropriate amount of time. This is a problem if there is insufficient spinning reserve and additional generation is needed quickly by the system. If generation does not come online in a timely manner, load shedding might become necessary. The first two problems are potentially damaging to generator equipment and effect power quality, while the third problem can cause a loss of load which might be considered the most severe of all three. While Figure 3.4 showed the normal synchronization process taking less than 6 seconds, the example given in Figure 3.5 exhibits prolonged synchronization taking over 30 seconds. This figure also shows how the generator frequency is constantly hunting the variable system frequency. As a result, their phase difference is too high for synchronization to occur. Hunting results from the total delay in common synchronizer control loops as shown in Figure 3.3. Simply put, by the time generator gets to the right position at the right time, system conditions have changed significantly.

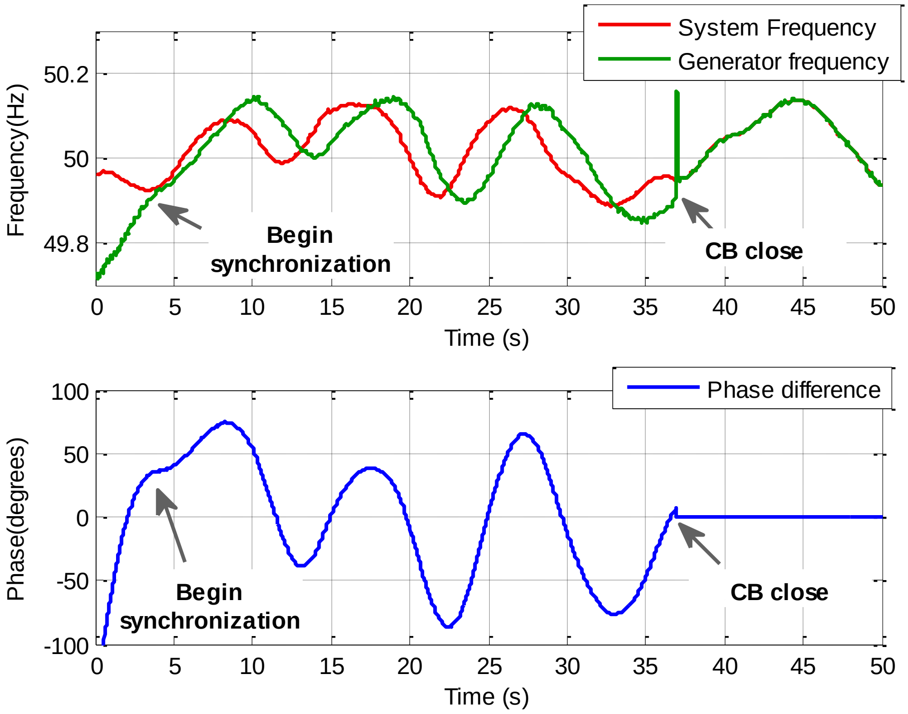

Figure 3.5. Example of a prolonged synchronization. Synchronization can only occur when the phase difference is within allowed limits (usually $\pm 10°$ phase) for a defined amount of time (usually 500 ms). Data for this example is taken from the case study system, described in section 3.3.

Prolonged synchronization might not be a big problem in systems where customer load changes slowly as shown in Figure 3.1. However, when the load, as seen by the generators, changes faster than the generators can potentially respond because of long synchronization times as shown in Figure 3.2, it is easy to see that the entire power system can become unstable. Another difference between the synchronization processes presented in Figure 3.4 and Figure 3.5 is the variation in system frequency. Based on these two graphs, we can conclude that a synchronization process necessarily takes longer in systems with high frequency variability, which includes most systems with high wind penetration (the amount of instantaneous power produced by wind turbines, compared to the entire power system demand, usually presented as percentage). Synchronization measurements taken over several years clearly show this trend as seen in Figure 3.6.

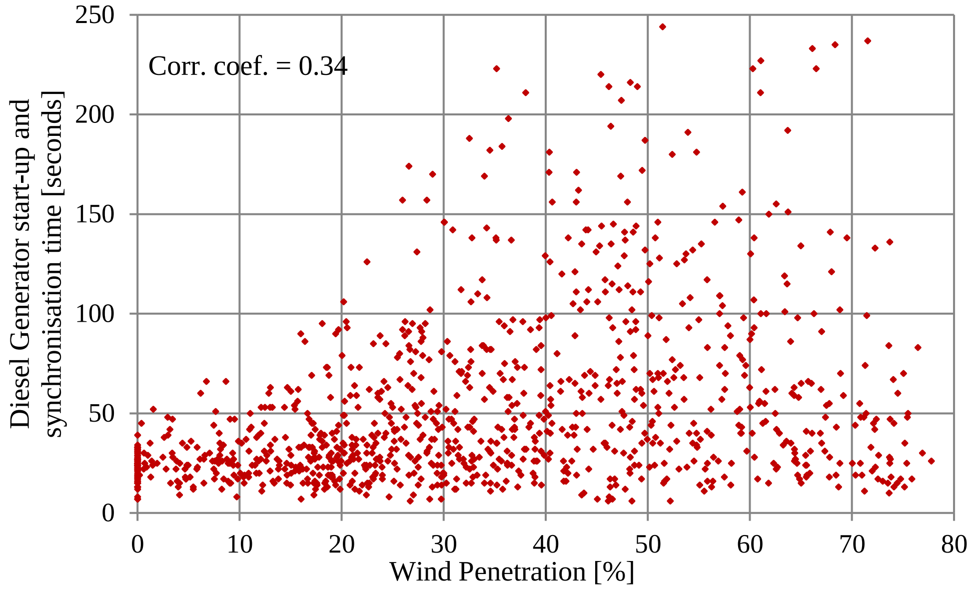

Figure 3.6. Diesel generator synchronization times increase as a function of wind penetration. A positive correlation coefficient (r=0.34), followed by a high correlation significance (p<0.001) shows a strong correlation between two series. Data for this example is taken from our case study system, described in Section 3.3.

The data for Figure 3.6 comes from a single generator over a one-year period. During that time 1,075 synchronizations were recorded and their duration times compared against recorded wind penetration levels. At low RE levels synchronization times are also lower. At high RE levels some synchronizations take several minutes. During the same year, observed IPS recorded 10 under-frequency load shedding events which were probably caused by insufficient generation during high wind penetration levels.

3.2. Predictive Synchronization Method

While high wind penetration has clear operation benefits from reduced costs and emissions, it is also prolonging the synchronization process of diesel generators and compromising power system stability. To maintain high wind utilization while avoiding hunting problems for synchronizing generators, predictive synchronizer model was developed (Figure 3.7) to reduce synchronization times.

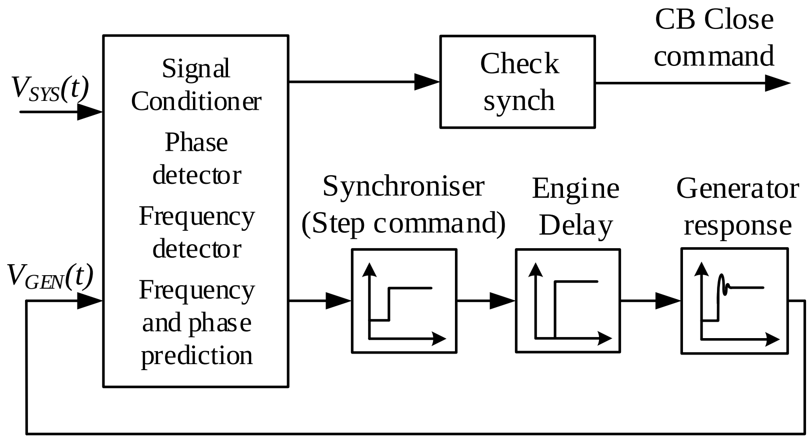

Figure 3.7. Functional diagram of the predictive synchronizer control loop. Detailed MATLAB Simulink model is provided in Appendix A.

The basic idea of our predictive synchronizer is to predict the frequency and phase of the system two seconds into the future and then set the generator to meet that prediction. If the prediction is sufficiently accurate (e.g. $\pm 10°$ phase), hunting between the synchronizing diesel and the system will be avoided.

The predictive synchronizer presented in Figure 3.7 differs from conventional synchronizers in two ways:

a) It compares predicted, instead of current, frequency and phase signals to the power system frequency and phase. This is presented in Figure 3.7 as an additional functionality of the signal conditioning module.
b) It does not use a PID loop, but sends a step change into the governor speed reference signal. This is presented in the Figure 3.7 as a Step Command Module.

Engine time delay in Figure 3.7 is the same as diesel engine delay presented in Figure 3.3.

Operation of the predictive synchronizer can be described as a five-step process (Figure 3.8):

- At the start of the synchronization process, the system frequency (f_{SYS}), the synchronizing generator frequency (f_{GEN}) and their phases (φ_{SYS} and φ_{GEN}, respectively) are measured from voltage signals V_{SYS} and V_{GEN} at a specific time interval and recorded. (Figure 3.8(a) shows this for system frequency only.) The differences between the system and generator frequencies ($\Delta f = f_{SYS} - f_{GEN}$) and the system and generator phases ($\Delta\varphi = \varphi_{SYS} - \varphi_{GEN}$) are calculated.

- Based on the recorded time-series of the system frequency, $f_{SYS}(t-n),\dots,f_{SYS}(t-2), f_{SYS}(t-1), f_{SYS}(t)$ and the system phase, $\varphi_{SYS}(t-n),\dots,\varphi_{SYS}(t-2),\varphi_{SYS}(t-1),\varphi_{SYS}(t)$, a predictive module calculates the (very near) future values for the system frequency, $f_{SYS}(t+n)$ and its phase $\varphi_{SYS}(t+n)$, as presented in Figure 3.8(b). This figure practically shows system frequency brought a few seconds ahead in time based on the prediction.
- Using frequency and phase difference (Δf , $\Delta\phi$) plus the predicted values for system frequency and phase ($f_{SYS}(t\ +n)$, and $\phi_{SYS}(t\ +n)$), the speed reference signals for the synchronizing generator governor are calculated based on the equal area criterion [84] and issued to the governor. Because both frequency and phase need to be within allowed limits, the synchronizer will issue two speed step commands to the synchronizing generator governor. The first step shifts the generator phase to the desired value, while the second step puts the generator in the predicted position for synchronization. The two steps are communicated as a step-up signal issued at t_1, and a stepdown signal at t_2, (Figure 3.8(c)).
- After a short delay (engine delay in Figure 3.7), the generator responds to given speed correction commands from the synchronizer (Figure 3.8(d)).
- If the frequency and phase predictions are within allowable limits, this adjustment of the speed will result in matching generator frequency and phase to the system. Synchronization has been achieved, so the Check Synch module issues CB close signal at t_3 (Figure 3.8(e)) to bring the generator online.

The difference between a predictive and a conventional synchronizer used in IPSs would be an electronic module containing prediction algorithms and the method of issuing a speed bias signal from a synchronizer to a diesel generator governor. Preliminary estimations conducted by the authors indicate that the cost of such modifications would not be significant, and although the price of the predictive synchronizer would be higher than a conventional synchronizer, it still would remain under US $1,000.

Correct prediction of the system frequency and phase on a very short-term time scale is a vital part of the proposed approach to synchronization in IPSs. In this chapter, very short-term prediction is defined as look-ahead period of 2 seconds. However, there is no reliable system for very short-term time-series prediction.

Both the frequency and phase represent a time series which can be defined as a set of observations of a parameter, or set of parameters, taken at a number of time intervals. These intervals are usually (although not always) of a regular length. Real-world time series are diverse. Some time series data changes slowly and relatively smoothly, for example monthly electricity demand. Other time series can exhibit chaotic behaviour, making their prediction very challenging. A frequency time series of an IPS with high wind penetration, such as in Figure 3.5, possesses these characteristics.

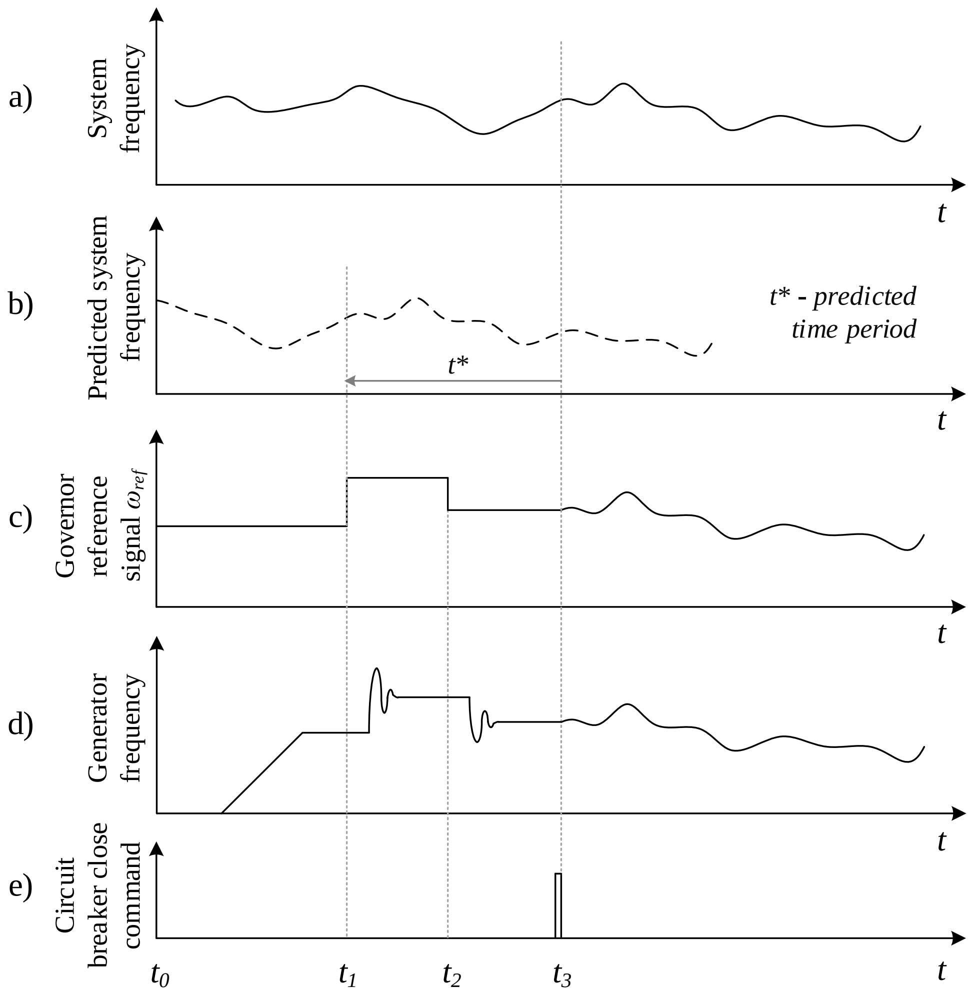

Figure 3.8. Operation of the predictive synchronizer.

The time scale is important when trying to create a prediction system. Two main classes of techniques have been used for very short-term predictions. These are statistical methods and methods based upon artificial neural networks (ANN). The statistical methods are auto-recursive. This means they use the difference between the predicted and actual values in the immediate past to tune the model parameters. The neural networks use past data taken over a longer time-frame to learn the relationship between the input data and output wind speeds. The accuracy of these methods degrades rapidly with increasing prediction lead time.

Prediction research is a growth area and increasingly often this research involves the use of artificial intelligence. In this Chapter, a hybrid approach was investigated – a combination of an ANN and fuzzy logic for very short-term system frequency and phase prediction.

Hardware Application

Conventional synchronizers have three main components: signal conditioning circuits (signal input), signal processing circuits and signal output components. The second component, signal-processing circuits, determines the action based on the input signal; this component presents the main difference between different types of synchronizers.

Analogue conventional synchronizers, which are often used in isolated power systems, are based on the basic electronic components. Digital, more advanced conventional synchronizers do have integrated chipsets and could be programmed to perform within given parameters. We envisage that a predictive synchronizer would require an integrated chipset capable of holding and processing a neural network. Given the progresses in computation technology, the required processor could come at a relatively low cost and could be installed instead of existing integrated chipsets of modern digital conventional synchronizers. Signal conditioning (input) and signal output circuitry used in digital conventional synchronizers could be retained. This would bring the production cost of a predictive synchronizer very close to the cost of conventional synchronizers.

Adaptive Neuro-Fuzzy System

The application of fuzzy (i.e. fuzzy logic based) and adaptive neuro-fuzzy (i.e. neural networks incorporating fuzzy logic) interference system (ANFIS) techniques to wind-diesel power systems has been proposed by several authors [85-87]. Previous work in this area has used fuzzy control algorithms during periods of high wind penetration to decrease the variability of RE or to better position diesel generation. Fuzzy systems showed better performance over standard PID control techniques in all instances.

Approach in this chapter is to use fuzzy techniques to control the synchronizing generator so that it can better cope with highly variable system frequency during the synchronization process. A prediction technique which would work for non-linear systems was developed [88]. As this prediction technique had success with a similar problem relating to short-term wind speed, ANFIS techniques were applied to this new prediction problem. The approach is to extend the techniques used to perform short term forecasting of variable wind speeds to enable forecasting of frequency and phase variation in an IPS.

To predict system frequency and phase, two ANFIS systems were developed, one for frequency prediction and another for phase prediction.

Fuzzy systems and neural networks are complementary tools for building intelligent systems. While neural networks are low-level computational structures that perform well when dealing with raw data, fuzzy logic deals with reasoning on a higher level. However, fuzzy systems lack the ability to learn and cannot adjust themselves. The combination of a neural network with a fuzzy logic into one integrated system therefore offers a promising approach to building very short-term wind prediction models. A neuro-fuzzy system is, in fact, a neural network that is functionally equivalent to a fuzzy inference model.

The ANFIS model proposed by Roger Jang [89] is a six-layer feed-forward neural network. The ANFIS structure is presented in Figure 3.9. For simplicity, it is assumed that the ANFIS has two inputs, x_1 and x_2, and one output, y. For additional simplicity each input is represented by only two fuzzy sets, although 3 or more are not uncommon. Extra membership functions will increase the accuracy of the results, but will take longer to train. For this example, the two fuzzy sets are converted to the output by a first-order polynomial.

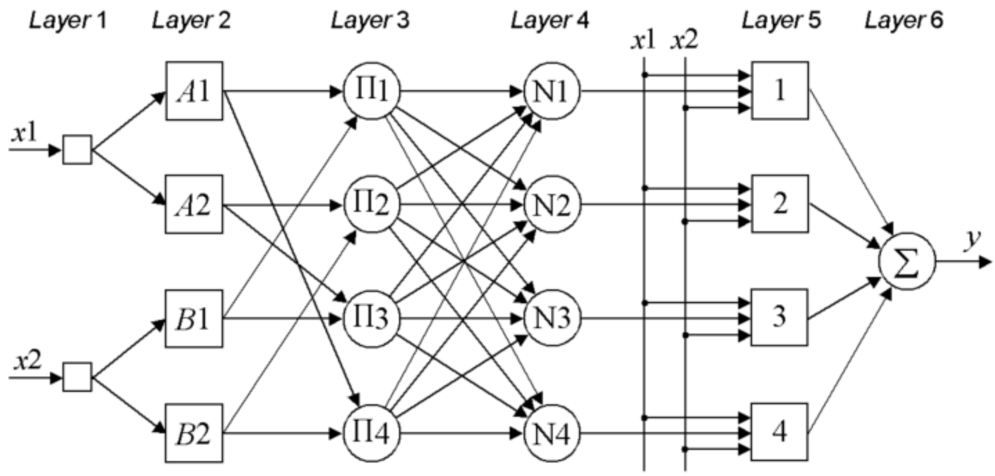

Figure 3.9. The ANFIS structure

The ANFIS in Figure 3.9 implements four rules, presented in Table 3.1:

Table 3.1. ANFIS Rules

IF x_1 is A1 AND x_2 is B1 THEN $y = f_1 = k_{10} + k_{11}x_1 + k_{12}x_2$	IF x_1 is A2 AND x_2 is B2 THEN $y = f_2 = k_{20} + k_{21}x_1 + k_{22}x_2$
IF x_1 is A2 AND x_2 is B1 THEN $y = f_3 = k_{30} + k_{31}x_1 + k_{32}x_2$	IF x_1 is A1 AND x_2 is B2 THEN $y = f_4 = k_{40} + k_{41}x_1 + k_{42}x_2$

where x_1, $x_2$are input variables; A1 and A2 are fuzzy sets on the universe of discourse X1; B1 and B2 are fuzzy sets on the universe of discourse X2; and $\{k_{i0}, k_{i1}, k_{i2}\}$ is a set of parameters specified for rule i.

Layer 1 is the input layer. Neurons in this layer simply pass external crisp signals to Layer 2.

Layer 2 is the fuzzification layer. Neurons in this layer perform fuzzification. In Jang's model, fuzzification neurons normally use a bell activation function.

Layer 3 is the rule layer. Each neuron in this layer corresponds to a single fuzzy rule. A rule neuron receives inputs from the respective fuzzification neurons and calculates the firing strength of the rule it represents.

Layer 4 is the normalization layer. Each neuron in this layer receives inputs from all neurons in the rule layer, and calculates the normalized firing strength of a given rule – the ratio of the firing strength of a given rule to the sum of firing strengths of all rules. It represents the contribution of a given rule to the final result.

Layer 5 is the de-fuzzification layer. Each neuron in this layer is connected to the respective normalization neuron, and also receives the initial inputs, x_1 and x_2. A de-fuzzification neuron calculates the weighted consequent value of a given rule.

Layer 6 is represented by a single summation neuron. This neuron calculates the sum of outputs of all de-fuzzification neurons and produces the overall ANFIS output, y.

An ANFIS uses a hybrid learning algorithm that combines the least-squares estimator and the gradient descent method [89]. First, initial activation functions are assigned to each membership neuron. The function centres of the neurons connected to input xi are set so that the domain of xi is divided equally, and the widths and slopes are set to allow sufficient overlapping of the respective functions. In the ANFIS training algorithm, each training epoch is composed from a forward pass and a backward pass. In the forward pass, a training set of input patterns (an input vector) is presented to the ANFIS, neuron outputs are calculated on the layer-by-layer basis, and rule consequent parameters are identified. A detailed ANFIS description is given in [90].

3.3. Case Study

Let us consider case study of King Island power system and measured and recorded results of diesel generator synchronisation.

King Island (KI) lies in the Bass Strait between Tasmania and the Australian mainland. It has a population of approximately 2000 people, and an economy based on agriculture and food processing. Customer load on KI ranges between 1 MW and 3 MW, with an average of around 1.5 MW. The KI power system is shown in Figure 3.10. There is one power station on the island with four distribution feeders delivering electricity to customers. The power station houses four diesel generators with a total generation capacity of 5.8 MW. Three diesel generators are rated at 1.6 MW and the fourth generator can deliver 1 MW. Three fixed speed (250 kW each) wind turbines are installed on a nearby hill, together with two larger turbines (850 kW each) with doubly fed induction generators.

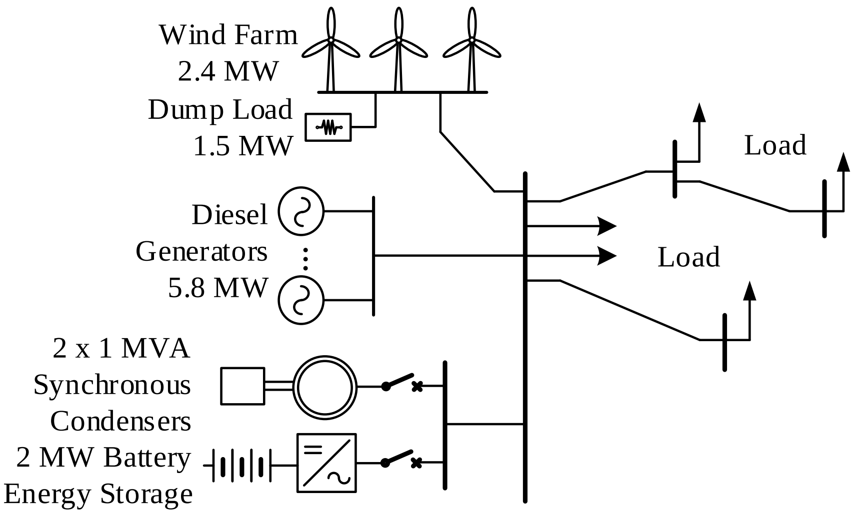

Figure 3.10. Schematic representation of the King Island power system

Data for Figure 3.6 was recorded during an entire year for one of King Island's diesel generators. This diesel generator is 2 MVA 50 Hz continuously rated generator. Other diesel generators are similar, from the same manufacturer and share similar characteristics.

Synchronizer settings are the same across all four generators. The synchronizing window is $\pm 10°$ of phase. Synchronizer dwell time defaults to a value of 0.5 seconds.

Wind turbines are not contributing to frequency control but are rather acting as a negative customer load. Dump Load presented in Figure 3.10 has the ability to control the frequency (resistive frequency control), and during this time diesel generators are placed in droop mode. It is interesting to note that with either diesel generators or dump load controlling the system frequency, intermittent wind output produces significant frequency deviations.

King Island system is operated automatically by a Programmable Logic Controller (PLC). The role of the controller is to properly schedule generation in the power system and to ensure that the quality and reliability of power supply is up to a standard.

When no renewable energy is present in the grid, the controller ensures that a sufficient amount of diesel generation is present in the system by monitoring the load and starting/stopping diesel generators accordingly. Controller does this by issuing a signal to a diesel generator synchronizer, which brings the generator onto the power system. By having enough generation capacity in the system, Controller ensures enough generation reserve is present in the system, if the load suddenly increases.

Wind is an intermittent source of renewable energy. As wind turbines power output depend on the immediate presence of the wind resource, the controller does not take entire wind generation capacity into account when calculating available generation reserve. A small portion of this available energy can be taken as firm generation, at a certain risk.

During high wind penetration periods, a higher portion of renewable generation can be taken as generation reserve. In fact, the controller can decide to switch off some diesel generation. At this moment, power system can find itself in a situation where running diesel generation is less than the entire power system load. At this time, the controller depends on renewable generation to cover the difference between what diesel generation can provide and what the load currently is. If the controller decides that variability of the wind resource is too high, it will attempt to start and synchronize another diesel generator.

As Figure 3.6 shows, the synchronization process during high wind penetration can sometimes take up to a couple of minutes. Since the wind resource is intermittent, it may slowly decay over a couple of minutes, where it will not be sufficient to cover the difference between the available running diesel generation and the load. At this moment, power system stability can be compromised. This is why timely operation of the diesel generator synchronizer is important in isolated power systems.

It is also worth mentioning that the controller helps maintaining power system stability during faults and transient processes. This is achieved by using under-frequency load shedding (UFLS), where some loads are disconnected, so most of the system load is preserved. Since dynamic processes during the fault conditions happen very quickly (in a matter of a few seconds), the synchronization process of diesel generators cannot be used.

The effectiveness of the predictive synchronizing technique was proven by running simulations and comparing results with the real and simulated conventional synchronizer.

Firstly, network frequency from our case study system was recorded in high speed (1 kHz) over a period of around 8 hours, during which wind penetration was about 30% of the consumer load. This real frequency data was later used as input data for the synchronizer model.

Secondly, the diesel generator described in Section 3.3. was modelled and used as a virtual generator to be controlled by a synchronizer in simulations. The generator model was verified against the actual generator sample data.

Next, three synchronizer models are built:

a) Model of a conventional synchronizer, explained in Section 3.1. This model represented the base case against which the predictive synchronizer models were compared. It was modelled using available manufacturer’s data [82], common MATLAB Simulink models and tuned using the recorded generator synchronization performance presented in Figure 3.6.
b) Model of a predictive synchronizer using a basic prediction technique - moving average. The purpose of this model was to compare the effectiveness of the synchronizer using more advanced prediction technique, ANFIS, to a synchronizer using moving average as a baseline prediction technique.

c) Model of a predictive synchronizer using ANFIS as a prediction technique. This predictive synchronizer model was firstly trained using a large set of frequency sample data collected from the case study system.

In three separate simulations for three different synchronizer models, all synchronizers were controlling a diesel generator which was constantly trying to synchronize to the system frequency. If it was unsuccessful, the synchronizer was restarted, and it went through another cycle. When it synchronized, synchronization was recorded, and the synchronizer was restarted for the next run.

The outcome of all performed simulations is presented in Table 3.2, and compared to recorded data from the case study system.

Table 3.2. Synchronization simulation results

#	**Type of synchronizer**	**Number of synchronizations**	**Median synchronization time**
1	Statistical data for conventional synchronizer (Figure 3.6)	1,075	42 seconds
2	Simulated data for a conventional synchroniser	681	44 seconds
3	Simulated data for the moving-average-based predictive synchronizer	937	32 seconds
4	Simulated data for the ANFIS-based predictive synchronizer	1,666	18 seconds

The first row shows results for a conventional synchronizer, from the case study system, presented in Section 3.3. This data set is also presented in Figure 3.6. Median synchronization time for the given data set was 42 s.

This conventional synchronizer is then simulated; it produces the median synchronization time of 44 s, which is very similar to the data recorded. These data also demonstrate the validity of the model.

Following this, a synchronizer using moving average as the basic prediction technique is simulated (presented in row 3 of Table 3.2). This simple prediction technique shows better performance than the conventional synchronizer.

Finally, a synchronizer using ANFIS as the prediction technique is simulated. The result shows the median average time of 18 s, which is an improvement when compared to both the conventional synchronizer and the simulated synchronizer with the basic prediction technique.

It is important to note that the simulation results show that a predictive synchronizer has achieved statistically better performance when compared with a conventional synchronizer. The presented result, however, does not imply that a predictive synchronizer will perform better in every possible scenario.

It is also interesting to compare prediction accuracy between the moving average and ANFIS prediction techniques. An example of prediction results for moving average and ANFIS are presented in Figure 3.11 and Figure 3.12 respectively. The same data sample is used for both prediction techniques, and resulted in moving average showing double frequency prediction error than ANFIS.

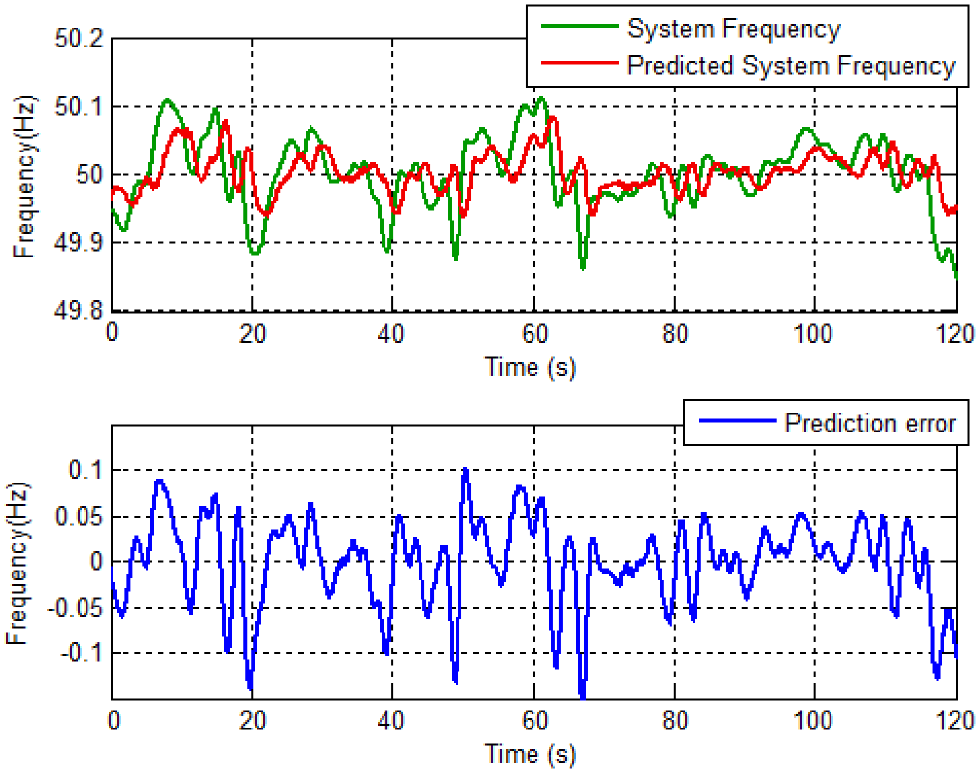

Figure 3.11. Moving average prediction results. Mean frequency prediction error was ~0.043Hz

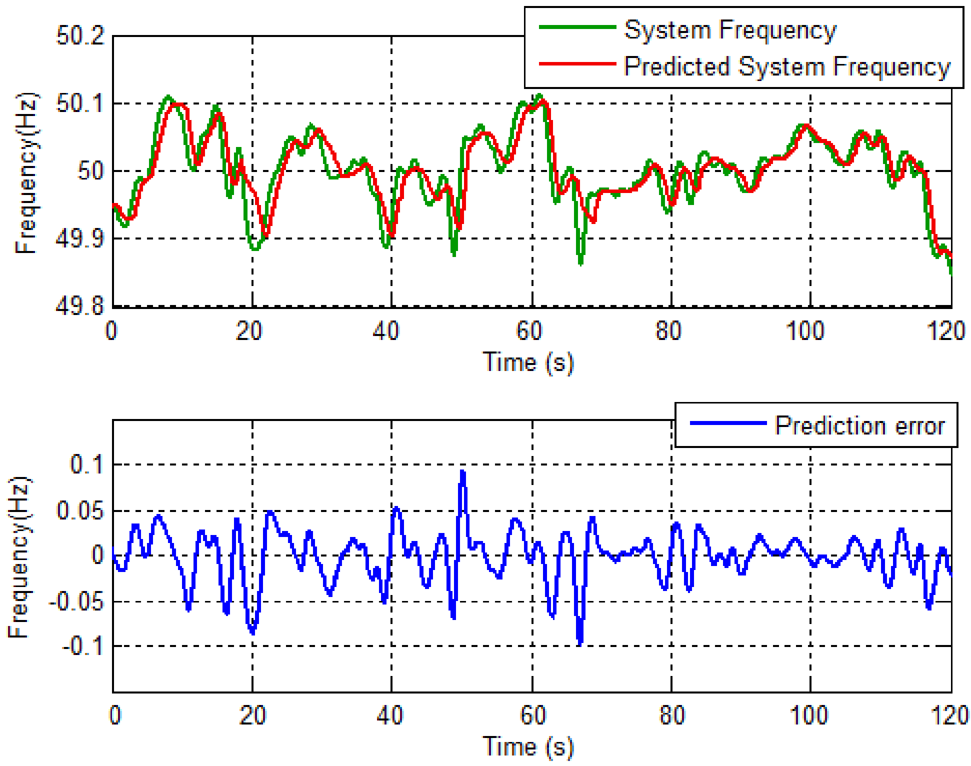

Figure 3.12. ANFIS prediction results and prediction error example. Mean frequency prediction error was ~0.019Hz

Although only frequency prediction examples were shown in Figure 3.11 and Figure 3.12, phase prediction shows similar results.

Two major conclusions could be drawn from Figure 3.11 and Figure 3.12:

a) ANFIS prediction technique is more suitable for use in predictive synchronization processes due to its higher prediction accuracy.
b) ANFIS technique is sufficiently accurate to be used in an IPS diesel generator synchronization process, as it decreases synchronization times and by doing so, increases system stability.

Finally, it is anticipated that further tuning of the ANFIS neural network, better processing power and future prediction techniques could yield even better results in subsequent prediction synchronizing devices.

3.4. Conclusion

This chapter identifies some of the synchronization challenges in IPSs with high wind penetration. As a solution to the problem of prolonged synchronization, the concept of predictive synchronization of diesel generators in these IPSs was proposed to be implemented in future synchronizers for diesel generators operating in high RE penetration IPSs. A model of a predictive synchronizer was developed and tested against recorded data of a real wind-diesel power system.

Simulation results have shown that a predictive synchronizer provides statistically better performance when compared to a conventional synchronizer. These results in significantly decreased synchronization times (on average) of a diesel generator during periods of high wind penetration.

Chapter 4. Fast demand response for achieving required level of spinning reserve

Chapter 4 has been removed for copyright or proprietary reasons.

Parts of this Chapter were previously published in:

Martin de Groot, **Dusan Nikolic**, James Forbes, “Demand Response in Isolated Power Systems”, Australasian Universities Power Engineering Conference, AUPEC 2013, Hobart, TAS, Australia, 29 September – 3 October 2013.

D. Nikolic, M. Negnevitsky, M. de Groot, S. Gamble, J. Forbes, M. Ross, “Fast Demand Response as an Enabling Technology for High Renewable Energy Penetration in Isolated Power Systems”, IEEE General Meeting 2014, Washington, July 2014.

Michael Negnevitsky, **Dusan Nikolic**, Martin de Groot, “The Smart Grid: Enabling Demand Response”, The Fifth International Conference on Smart Grids, Green Communications and IT Energy-aware Technologies, ENERGY 2015, May 24 - 29, 2015 - Rome, Italy.

Nikolic, D and Negnevitsky, M and de Groot, M and Gamble, S and Forbes, J and Ross, M, “Fast demand response as an enabling technology for high renewable energy penetration in isolated power systems”, Proceedings of the Cigre Session 2016, 21-26 August 2016, Paris, France, pp. 1-11. (2016)

Dusan Nikolic, Michael Negnevitsky, Martin de Groot, “Fast Demand Response as Spinning Reserve In Microgrids”, 10th Mediterranean Conference on Power Generation, Transmission, Distribution and Energy Conversion, Paper 082 Session S1.2, 6-9 November 2016, Belgrade, Serbia.

Chapter 5. Inertia requirements for isolated power systems under high renewable energy penetration

This thesis chapter has been previously published [9] in entirety:

Dusan Nikolic, Michael Negnevitsky, "Adding Inertia to Isolated Power Systems for 100% Renewable Operation," Proceedings from Applied Energy Symposium and Forum, Renewable Energy Integration with Mini/Microgrids, REM 2018, Rhodes, Greece, September 2018. Additionally, this paper has been invited for publication in Special Edition of Applied Energy, with paper final submission date of March 2019.

Some parts of this chapter were also previously published [7] in:

Dusan Nikolic, Michael Negnevitsky, “Practical Solution for the Low Inertia Problem in High Renewable Penetration Isolated Power systems”, Conference Proceedings, IEEE Power Energy Society General Meeting, August 5-9, Portland USA 2018.

Chapter short summary:

This chapter presents the concept of the synchronous renewable energy generator as an enabling technology supporting near-100% renewable energy systems with inertia and provision of fault currents. Synchronous renewable energy generator is a symbiosis of a synchronous machine (alternator) and battery energy storage which replaces diesel engine. This Chapter provides theoretical concept as well as some real-world measurements of such a system, under high renewable penetration conditions.

5.1. Introduction: Inertia in isolated power systems

This chapter presents a practical enabling technology in a form of synergy between a battery energy system and a synchronous machine, which can support fully renewable power system while providing nominal power system inertia. For simplicity, the case for this technology is presented on an example of an Isolated Power System with very high renewable energy contribution.

With the adoption of 2015 Paris Agreement, nations around the world set out targets for the reduction of GHG emissions, and with it, plans for transition to RE power systems. Some nations, such as Pacific countries, are directly threatened by raising sea levels and have decided to set bold renewable energy goals, aiming for 100% RE power systems and GHG emissions reduction by 2050 by latest (although smaller nations aim to reach that goal by 2030).

One of key lessons high RE penetration research in IPSs [5, 29, 96-98] has provided is that RE sources need complementary, or enabling, technologies to deal with the attendant issues of highly variable power output and low inertia. Examples of complementary technologies include: energy storage (e.g. battery energy storage [71], hydrogen [97], flywheels [29]), bio-diesel engines, fast acting demand response [5], better control systems [99]. While these technologies found their application, operation, maintenance and integration challenges still exist. Lately, advances in battery energy storage have shifted focus to this technology, more than any other. Control of batteries, or more precisely, inverters which connect battery storage to a power system was in research focus in the last decade. Advanced control strategies [100], synthetic inertia [101] and advanced inverter technologies [102] promise to solve the problem of low inertia in future RE power systems. Research has shown that inverters are capable complementing conventional generation in some cases, however, in power systems without conventional generation two main limitations of inverter technology are very much evident – no inertia, and low fault current provision capability.

The author of this thesis has worked in IPSs for a number of years, over which time he was exposed to some of the effects RE had on power system stability, and IPS operation. What was observed is that simple solutions, which mimic established routines produce excellent power system results are best received by power station operators. One of the best solutions introduced into IPS, was based on a synergy of new, fast acting battery energy system, and almost a century old technology – synchronous machines.

5.2. Concept of synchronous renewable energy generator

Stability of a power system relies on its generation to provide real and reactive power, provision of frequency and voltage control, provision of inertia, provision of fault currents and non-intermittent power supply. Modern research is pursuing improvements in inverter technologies, with goal of having a device capable of providing all the above power system services. Presently, this solution remains elusive, while nations are more aggressively pursuing higher RE penetrations, leaving power systems vulnerable to RE intermittency more than ever before. Alternative to inverter-only solution is a solution of synergy between an inverter and a synchronous machine.

5.2.1. Traditional governing of IPSs

IPS are traditionally powered by diesel generators which can provide all power system services. Diesel generator (Figure 5.1) is a device which represents a synergy between a diesel engine (a) and a synchronous machine – alternator (b) which is connected to the grid. Positive side of diesel generator technology is that it is a device capable of providing all power system services to an IPS. Some of its characteristics are:

- Provides real power in range of 30 to 100% of its rated capacity [103].
- It can be overloaded of up to additional 10%, for limited periods of time.
- It can respond to a load step of up to 100% of its rated capacity.
- Engines could be started in under 10 seconds, provided they have been kept warm.
- They consume diesel fuel, and are a source of GHG, and frequent oil and fuel spills.

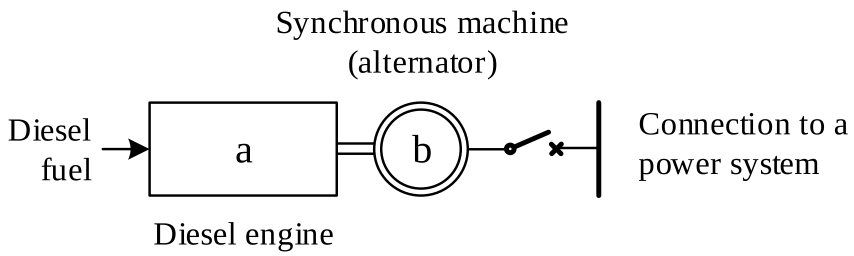

Figure 5.1 Simple presentation of a traditional diesel generator main components.

5.2.2. Proposed new synchronous RE generator

If a battery energy storage is coupled with a synchronous condenser, it forms a synergy device which behaves like a synchronous RE generator (Figure 5.2). It consists of a synchronous machine (such as described by [63]) (b), which is started by a small pony motor (a), very short-term power battery (<5min) (c) and a DC/AC inverter (d). While a synchronous RE generator consists of established technologies, it controls them only to mirror operation of a typical diesel generator.

Advantages of synchronous RE generator over a battery energy storage system lie in provision of system inertia and fault currents, services typical inverters cannot provide. Advantage over diesel generators is in utilization of stored RE and environmentally friendly operation. Using the inverter instead of a diesel engine gives synchronous RE generator ability to generate in the whole 0 to 100% range. Inverters usually have higher overload capability than diesel engines and they respond much faster than diesel generators.

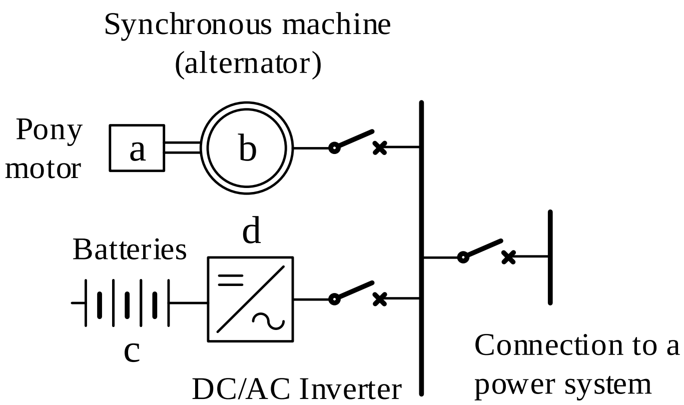

Figure 5.2 Simple presentation of a Synchronous RE generator main components.

Operation of the new synchronous RE generator is as follows:

1. When offline, synchronous machine as at standstill, and battery energy system is not online.
2. When starting up, pony motor is used to speed up the synchronous machine and synchronise it to a power system. At the same time, battery energy system is synchronised, but does not produce or consume power. Energy needed to start and synchronise the synchronous machine is taken from the power system.

3. While operating and synchronised to a system, synchronous machine mimics behaviour of a diesel generator alternator, such that it provides inertia to a power system, it can provide fault currents when necessary, and can generate or consume reactive energy.
4. During 100% renewable operation, battery energy system would control the frequency via its inverter by consuming and producing small amounts of real power. Synchronous machine would still behave as described in step 3. Synchronous machine and inverter losses are covered by energy taken from the power system, which would usually come from surplus RE generation.
5. At the moment of sudden drop of renewable generation, battery energy system would immediately increase its input to cover the missing generation. At the same time, a standby diesel generator would be dispatched, which would typically synchronise within 1-2 minutes. When an incoming diesel generator synchronises, synchronous RE generator operation reverts to step 2 or is completely shut down (step 1).

Some of the limitations of this technology are:

- Complexity of the solution requiring sophisticated control system for control of two separate devices,
- Ability to operate in generation mode only with a sufficient battery state of charge,
- Need for modestly higher skilled operation and maintenance crews.

5.2.3. Sizing of the new synchronous RE generator

The function of a synchronous RE generator is to provide system services such as inertia and fault currents in a manner which mimics conventional diesel generators.

If a synchronous RE generator is to simply replace the functionality of a diesel generator, its battery energy system could be sized to mirror one of the IPSs' diesel generator's engine power rating, and its synchronous condenser could be designed with a similar inertia to that of a diesel generator.

Each IPS has its own performance criteria such as allowable rate of change of frequency, minimum and maximum allowable frequency, all of which influence the selection of required inertia. An opportunity synchronous RE generator provides is ability to size battery energy system capacity and inertia capacity separately, to suit specific IPS' performance criteria. This is possible as synchronous RE generator physically decouples prime mover (battery energy system) from the synchronous machine. Standard diesel generators do not enjoy this flexibility.

While standard diesel generators are built with typical inertia values (with inertia constant H typically in the range of 0.3 to 0.6 seconds [103]) intended for diesel-only generation IPSs, engineers planning RE IPS have the opportunity to design systems with size of a battery energy system and synchronous machine inertia constants best suited for each IPS's specific needs.

5.2.4. Synchronous RE generator cost and LCOE impact

As previously mentioned, cost of a synchronous machine is around $0.3/W, while capital cost of a chemical battery could be assumed as $1/W. Together, they form a synchronous RE generator. With the added complexity and cost of a new controller total cost can be assumed up to $1.5/W. This capital equipment cost is 50% higher than typical installed diesel generator cost in remote IPS of about $1/W.

Functionality of a synchronous RE generator could be replicated by either a low load diesel generator capable of operating at 0% loading continuously, or a battery energy system capable of providing high fault currents, comparable to a synchronous machine.

First solution using low-load diesel generator would constantly consume diesel fuel, which would greatly increase overall diesel fuel consumption over longer periods of time. Second solution using batteries would require inverter to provide comparable fault currents to that of a synchronous machine. Typical diesel generators provide between fault currents up to 5-7 per unit, therefore battery inverter would have to be oversized, which would increase the capital cost of the battery system to 5-7 times higher than originally assumed $1/W.

As enabling technologies do not directly contribute to production of power their contribution to LCOE is harder to estimate. However, comparing synchronous RE generator, low-load diesel generators and sole battery energy systems, it could be observed that synchronous RE generator would perform for the lowest capital vs ongoing cost, and consequently, contribute to the lowest LCOE.

5.3. Case study system and measurements

Case study system was presented in Section 3.3.

5.3.1. Case study measurements

The measurements from the case study system which demonstrate behaviour of the system with high renewable penetration, in the presence of large-inertia SC and a BES system, are presented. Figure 5.3 presents high speed measurements (sampled at 1 kHz, with a duration of 90 seconds) during a synchronisation of the SC to a power system run by one diesel generator. The SC synchronises to the grid at 60th second in Figure 5.3, and adds to the system inertia. Figure 5.4 presents power system operation during high renewable penetration after the shutdown of the last diesel generator (sampled at 1 Hz, for about 1 hour).

During the period presented in Figure 5.4, renewable generation was around or above the power system load. Synchronous RE generator (SC and BES) were present in the system. Initially, with a diesel generator present, BES was charged on surplus renewable energy. When diesel generator shut down around 1,100 seconds into the measurement, BES was managing variability of renewable power output and regulating system frequency. SC was providing system inertia while consuming about 100 kW for its losses. Figure 5.4 measurement demonstrates that a stable operation of a megawatt – scale power system can be maintained for prolonged periods of time without diesel generation, with a presence of a synchronous RE generator.

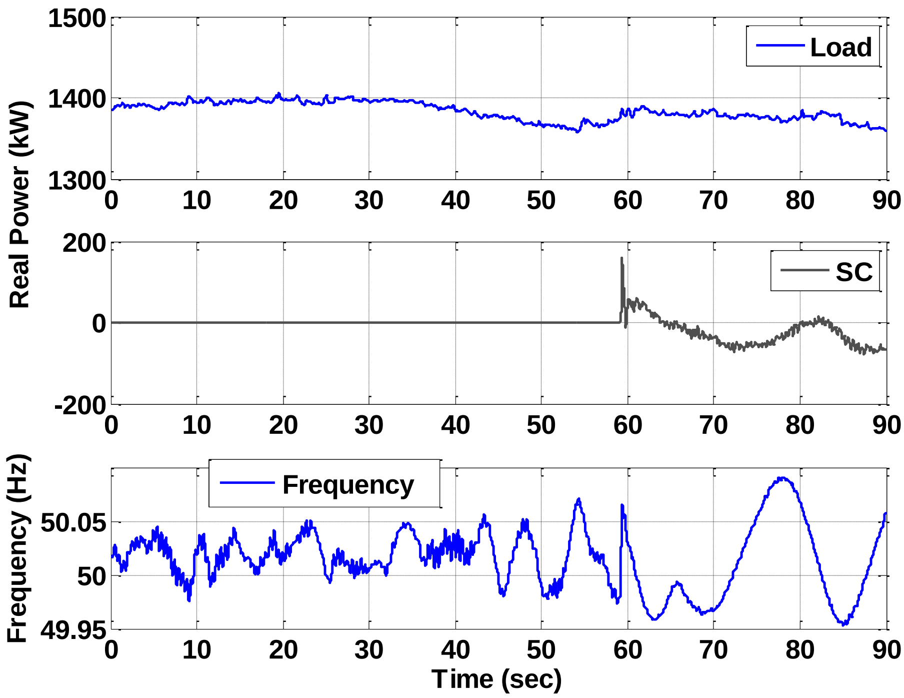

Figure 5.3 Measurement data showing synchronisation of a Synchronous Condenser (SC) to the grid.

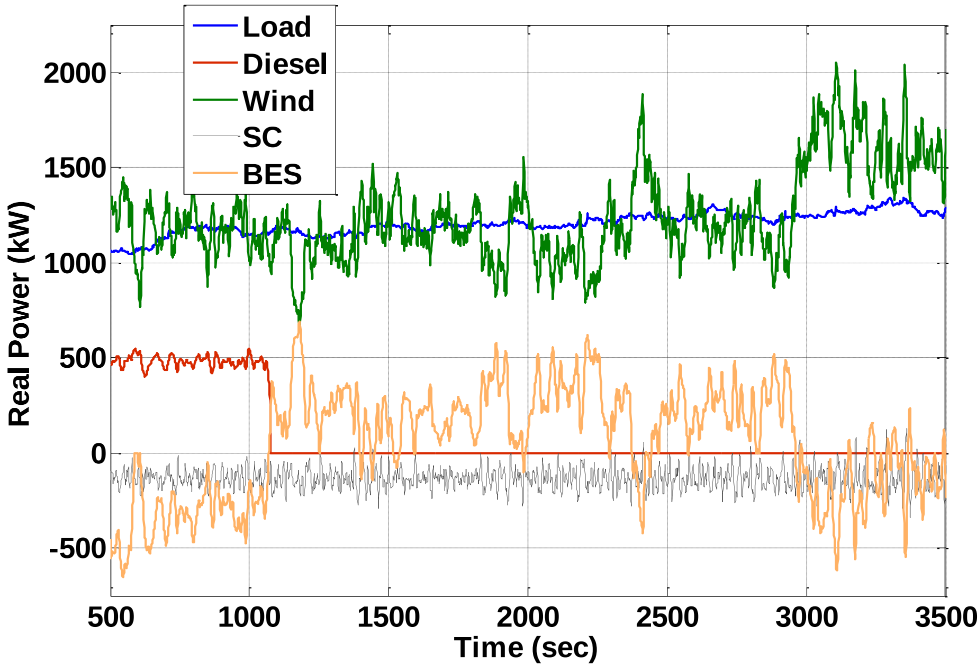

Figure 5.4 Measurement data for transition into fully renewable generation.

Finally, Figure 5.5 presents high speed measurement (sampled at 1 kHz, with a duration of 60 seconds) of distribution faults during the renewable operation of the King Island IPS (no diesel generation).

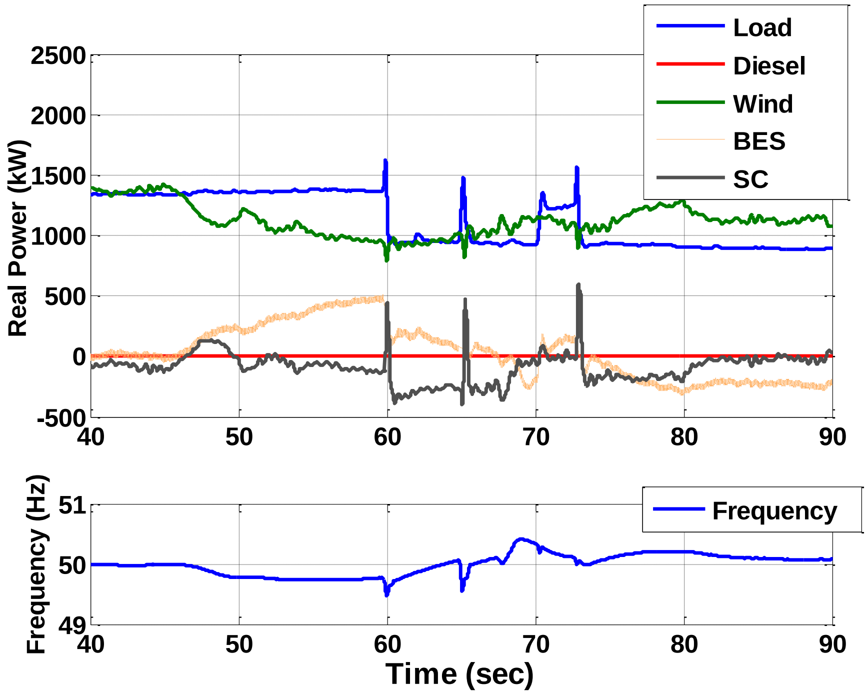

Figure 5.5 Measurement data showing Synchronous Condensers (SC) responding to distribution faults.

Around 60th second of the measurement, a fault occurred on one of King Island IPS's feeders which caused it to trip. Five seconds later, feeder reconnected but tripped again. Another five seconds later, feeder re-connected, but tripped once again about three seconds later. During this time, renewable energy generation was covering most of the load, while the BES was supplying the difference. Diesel generation was shut down during the entire measurement. This measurement presents that a megawatt-scale power system operating at high renewable penetration levels can maintain power system stability during adverse power system events, with a presence of a synchronous RE generator.

5.4. Discussion

In traditional IPSs, diesel generators are usually the main source of electric energy and they regulate the system frequency and voltage. They are also the main source of system inertia. Most of the diesel generator inertia is stored in its alternator [103], or the synchronous machine part of the genset, while rotating parts of diesel engine contribute to the genset inertia with much less. Hence, most of a diesel generator inertia could be mimicked by the inertia of a synchronous condenser.

Diesel generators are devices capable of providing all services a power system needs; however, this comes with an ecological price. In contrast, synchronous RE generator (BES and SC) can provide all the services diesel generator provides. To support technical statements from Section 5.2. , this chapter presented real-world measurement taken from the case study system. Measurements clearly demonstrate that synchronous RE generators:

- Could bring inertia to a power system, comparable (or even higher) to inertia, which is provided by traditional diesel generators,
- Can maintain power system stability, frequency and voltage with no diesel generator present, and
- Can supply fault currents necessary for clearing of distribution faults, without the need for diesel generators.

In addition to technical comparisons with traditional diesel generators, the cost of energy from a synchronous RE generator is discussed to be lower than from a diesel generator, but without GHG emissions.

Negative sides to a synchronous RE generator were mentioned as higher complexity than diesel generators; they would require higher skilled staff and larger installation space. Synchronous RE generator does not generate electric energy but uses some of the power generated elsewhere to cover its operational losses. Therefore, this technology is best used in high RE penetration systems which experience high renewable energy surplus. In conclusion, synchronous RE generator is an environmentally friendly technology which enables IPSs to operate at very high or entirely renewable energy penetration levels, while enjoying the power system stability once provided by conventional diesel generation.

5.5. Conclusion

With the power industry being one of the major contributors to global warming, a sense of urgency is imposed on policy makers and power system operators to accept further RE generation. Enabling technologies which mitigate negative effects from RE generators are showing mixed techno-economic results. One of the prime enabling technology candidates, battery energy storage technology promises a lot, but is still in development, and cannot fully supplement RE generators in power systems.

Enabling technologies which leverage both positive sides of energy storage and synchronous generation is a synergy of a synchronous machine and a battery energy storage, called synchronous RE generator. Crucial difference between the sum (synchronous RE generator) and its parts (battery energy system and synchronous machine) is that operation of a synchronous RE generator is controlled that is mimics operation of a conventional diesel generator. By doing so, it offers all the benefits diesel generators provide, without diesel fuel consumption.

This renewable technology does not produce any GHG emissions and provides a power system with all necessary services. The technology is proven through a multi-year operation in an IPS of King Island in Australia. This chapter presented arguments for utilization of this technology in IPS under high RE penetration. It also presented some real-world measurements of an operation of such system under adverse power system conditions and demonstrated its value in high renewable power systems.

Chapter 6. Summary and future directions

6.1. Thesis Summary

Isolated Power Systems supply electric energy to customers living in remote areas across the world. Traditionally, electric energy is produced using diesel generators, which are convenient, but produce several problems for the isolated communities:

- High cost of energy – with ever rising diesel fuel prices, remote communities see a portion of their earnings go to distributers of fossil fuels,
- Energy dependence – fossil fuels are intrinsically connected with global political trends, and isolated communities are affected by trends they cannot control,
- Poor quality of energy – paired with lack of technical skill, remoteness and usually, harsh conditions, quality of energy in isolated power systems is usually much lower than in larger, interconnected systems, and
- Pollution – many low-lying island countries are facing a real threat of rising sea level and are very concerned about the emissions their generating sources produce.

Renewable energy sources offer some of the solutions to the problems isolated communities face. Renewable energy generators often produce energy at a lower cost than diesel generators, they provide energy independence as local energy resources are used and produce very small amount or no polluting emissions at all.

Renewable energy generation also brings challenges to the isolated communities, such as:

- Power system stability challenges, due to renewable energy intermittency,
- Having higher capital cost than diesel generation,
- They require larger land or sea areas, due to their inherent lower energy density, and
- Higher technical skill level as new technologies are more complex and potentially harder to operate and maintain.

This thesis focused on the first two challenges renewable energy sources bring to power systems, power system stability and cost of energy. This was summarised in Thesis overall goal – “To develop lower-cost enabling technology alternatives which could fast track isolated power systems to higher renewable energy penetration levels”.

Material presented in this Thesis answered to the Thesis overall goal by establishing a five-step framework for transition of isolated power systems from diesel-only to nearly 100% renewable operation, and by setting three research aims which focused on specific technical solutions to challenges in the last three steps of the proposed framework.

The five-step framework was described as:

1. Systems with no or very low RE generation in power system are powered by diesel generators,
2. Systems with smaller amounts of renewable generation usually perceive them as load offset, and do not experience major disruptions,
3. Systems with larger amounts of renewable energy are the first to experience RE integration issues. Here, high renewable energy penetration pushes diesel generation to its limits, and often requires some of it to be switched off. Supplementary technologies which enable this high renewable penetration are dubbed enabling technologies and together with some diesel generation regulate RE intermittency,
4. Systems with high amounts of renewable energy contribution usually incorporate enabling technologies which enable them to operate without diesel generation under favourable RE and system conditions for limited amounts of time, and
5. Systems with 100% or near-100% RE generation can run with RE generation only for prolonged periods of time and rely on diesel generation for emergency back-up only.

Steps 3 and 4 in the Five-step framework are when enabling technologies are introduced and scaled up, therefore these two stages pose the greatest technical challenge.

From there, three Thesis aims were established which propose enabling technologies which contribute to high RE penetration during steps 3 and 4:

1) Development of cost-effective technology for synchronisation of diesel generators in IPS during periods of high RE penetration and high RE generation intermittency,
2) Development of fast demand response for supporting high RE penetration by rapidly controlling part of the load and adding to power system spinning reserve, and
3) Development of enabling technology which provides sufficient level of power system inertia to high RE penetration IPSs and rapid real power support during lulls of RE generation.

First Thesis Aim was described and achieved in Chapter 3. Here, isolated power systems in the step 3 of the proposed framework operate with less diesel generation than required for supply of the total instantaneous power system load, during times of abundant RE generation. In case of rapid drop of RE generation, stand-by diesel generation needs to be quickly brought on-line. The challenge here is that during RE generation drop, its high intermittency affects power system frequency which starts to deviate off its nominal value and makes it harder for diesel generation to synchronise.

Predictive synchroniser enabling technology is proposed as a solution for this problem and described in Chapter 3. Using neural networks for power system frequency and phase forecasting, predictive synchroniser is capable of synchronising diesel generators in less time than conventional synchronisers, and bring stand-by diesel generation online faster, when it is needed the most.

Once isolated power systems transition into step 4 of the proposed framework, they can run without diesel generation for limited amounts of time. Extending the time with diesel-off generation has a positive impact on lower cost of energy and lower emissions. An enabling technology which helps isolated power systems extend diesel-off operation is outlined in Chapter 4.

Broadly speaking, an isolated power system can enter diesel-off operation when RE generation exceeds instantaneous power system load. Power systems can stay in this state, if there is sufficient RE generation. However, due to sudden changes in RE resource (such as a wind lull or a passing cloud), RE generation can decrease under its necessary levels and diesel-off operation may be interrupted. Sometime, this RE generation deficiency is very short, nevertheless it interrupts diesel-off operation and diesel generation is brought online to support the system.

The solution proposed in Chapter 4. proposes controlling power system load during times of RE generation deficiency. When RE generation drops, if some of the load can be switched off, total load could still be lower than total RE generation, which implies that diesel-off operation can be continued. The challenge with such enabling technology is speed. RE generation can radically drop in a matter of seconds, which is why power system load must be controlled within the same or shorter timeframe. Fast aggregated demand response is therefore proposed and demonstrated in Chapter 4. as enabling technology which can aggregate and control distributed loads in sub-second timeframes. As such, it was demonstrated capable of supporting high RE penetration isolated power systems during times of short and sudden lulls of RE generation.

One of the greatest challenges to isolated power systems capable of transitioning into diesel-off operation is provision of power system services such as power system inertia or fault currents. Diesel generators have synchronous machines which are very good of providing these services, however during diesel-off operation, they are not operating in a system.

Chapter 5. proposes a step 4 and step 5 enabling technology which can provide required power system services, without diesel generation, in a form of a symbiosis between a synchronous condenser (synchronous machine) which acts as an alternator of a diesel generator, and fast-acting battery energy storage, which acts as diesel engine and can provide rapid active power support. Chapter 5. provided a description of this enabling technology and measurement results which proved that synchronous condenser does add inertia to the power system, can provide adequate amounts of fault current and can effectively replace diesel generation if its battery energy source allows it to. By doing so, it greatly contributes to IPS stability and extends diesel-off operation.

Isolated power systems see RE technologies as a solution to the problems they are facing, however RE generation introduce new technical challenges in those systems. As such, they require supplementary enabling technologies which enable IPS to enter and sustain diesel-off operation while providing required levels of power system stability, quality of electric energy and reliability of power supply.

Three enabling technologies described in this thesis are designed to provide required level of support to RE generation in IPS and have demonstrated its effectiveness through real-world IPS measurements.

As such, enabling technology solutions proposed in this thesis fully respond to established aims and the overall goal.

6.2. Future Directions

Future research will focus on further improvements of the proposed enabling technologies:

- Future IPSs could see communications infrastructure rolled out in conjunction with electric energy infrastructure. This approach would reduce cost of smart grids and would provide a segway into control of more customer loads and distributed residential and commercial renewable generation.

- Emergence of electric cars and other transportation vehicles would mean introduction of a new type of load into future IPSs. Using communication pathways to control charging of these vehicles during times of RE generation surplus would greatly help the RE generation and enabling technologies infrastructure – as more energy is used, the cost of energy is reduced. It would also benefit the overall isolated community emissions, as more electric vehicles would mean further reduction in GHG emissions.

- A new synchronous condenser-battery energy storage technology which would firmly incorporate battery energy storage and synchronous machine, reduce losses and reduce integration issues between those two technologies.

- Microgrids are a term increasingly used in the interconnected power systems. The future of conventional power systems could be related to control of a larger number of microgrids capable of connecting or disconnecting from it. When disconnected, by definition, each microgrid would become an Isolated Power System, with similar challenges to remote ISPs. Additionally, some microgrids could be disconnected from the main grid, but stay connected to each other, and while doing so, could potentially share energy and power system services. Future research will focus on this new breed of enabling technologies capable of facilitating this new state of the conventional power systems.

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A. Appendix – Predictive Synchronisation MATLAB Simulink model

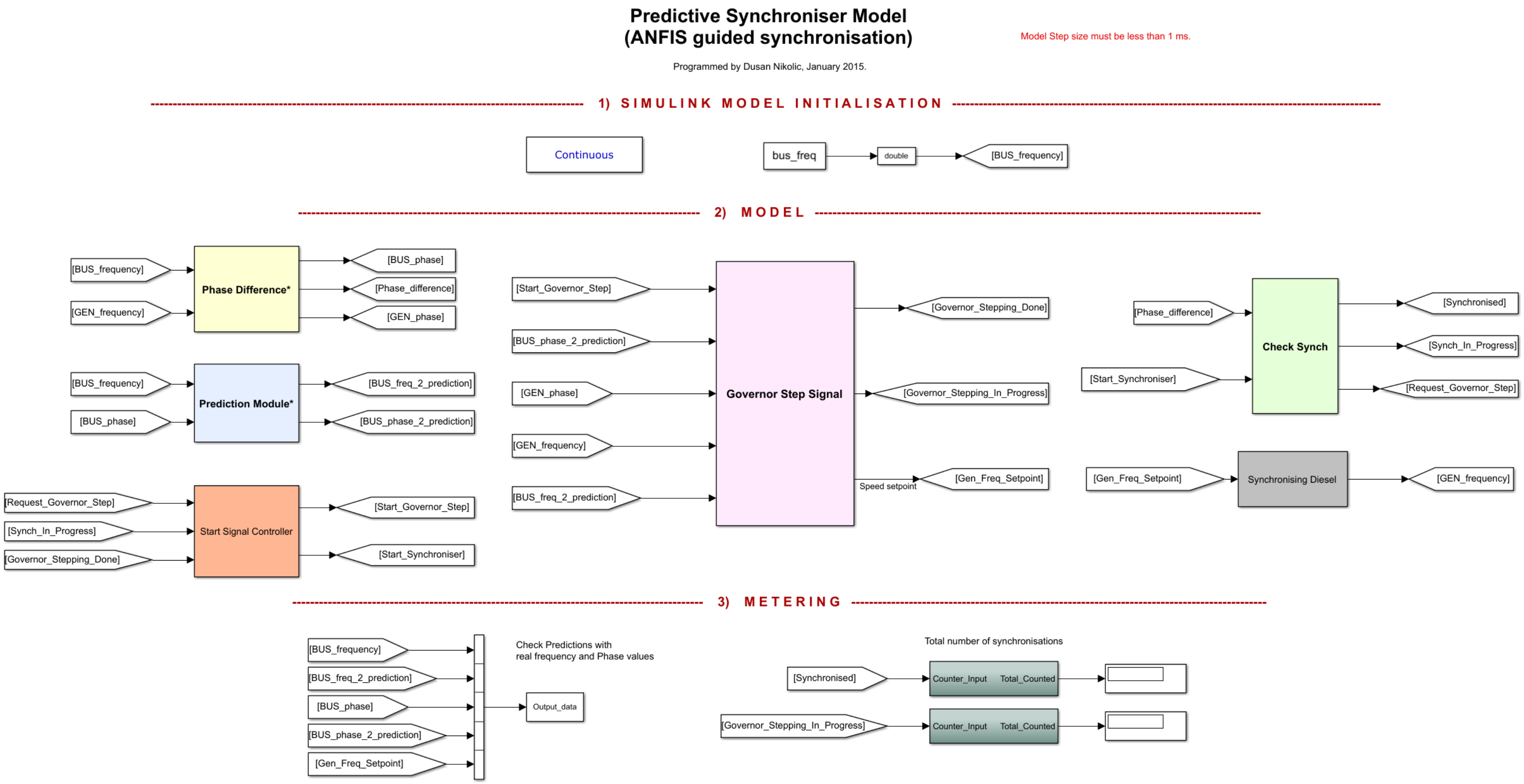

Figure A.1. Predictive Synchroniser Simulink Model. The model consists of the 'Phase Difference Module', 'Prediction Module', 'Starts Signal Controller', 'Governor Step Signal Module', 'Check Synch Module' and Synchronising Diesel Module' all of which are described in further figures.

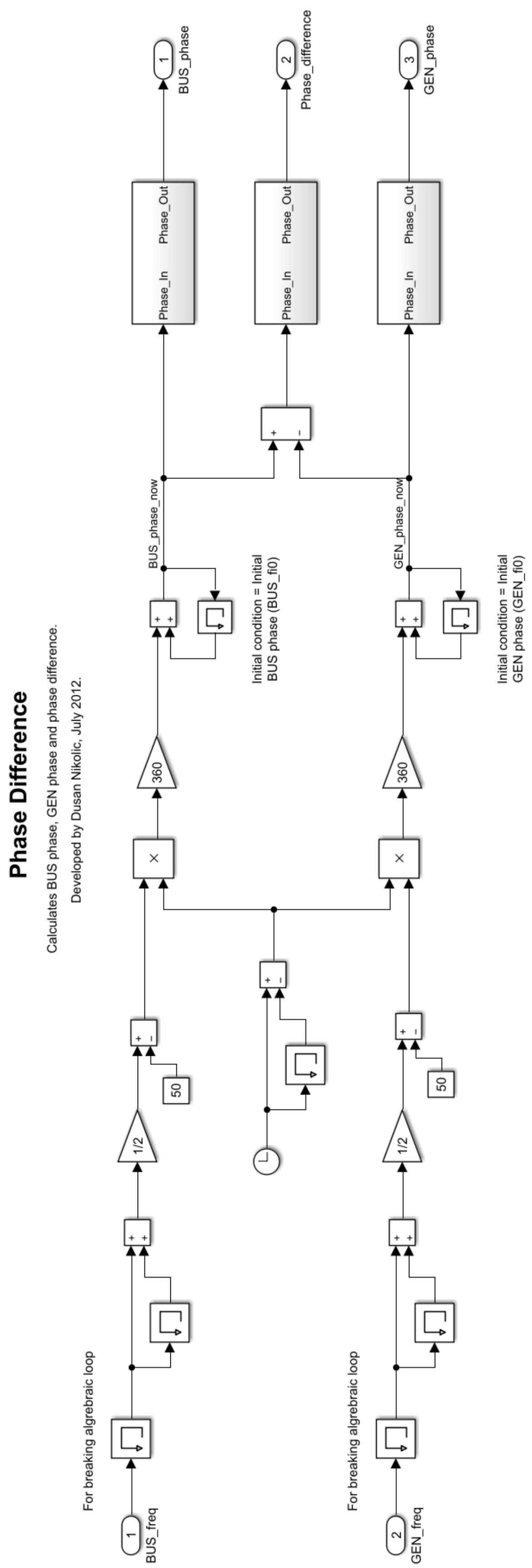

Figure A.2. Phase Difference Module MATLAB Simulink model. This module calculates both system and Generator phases and their difference

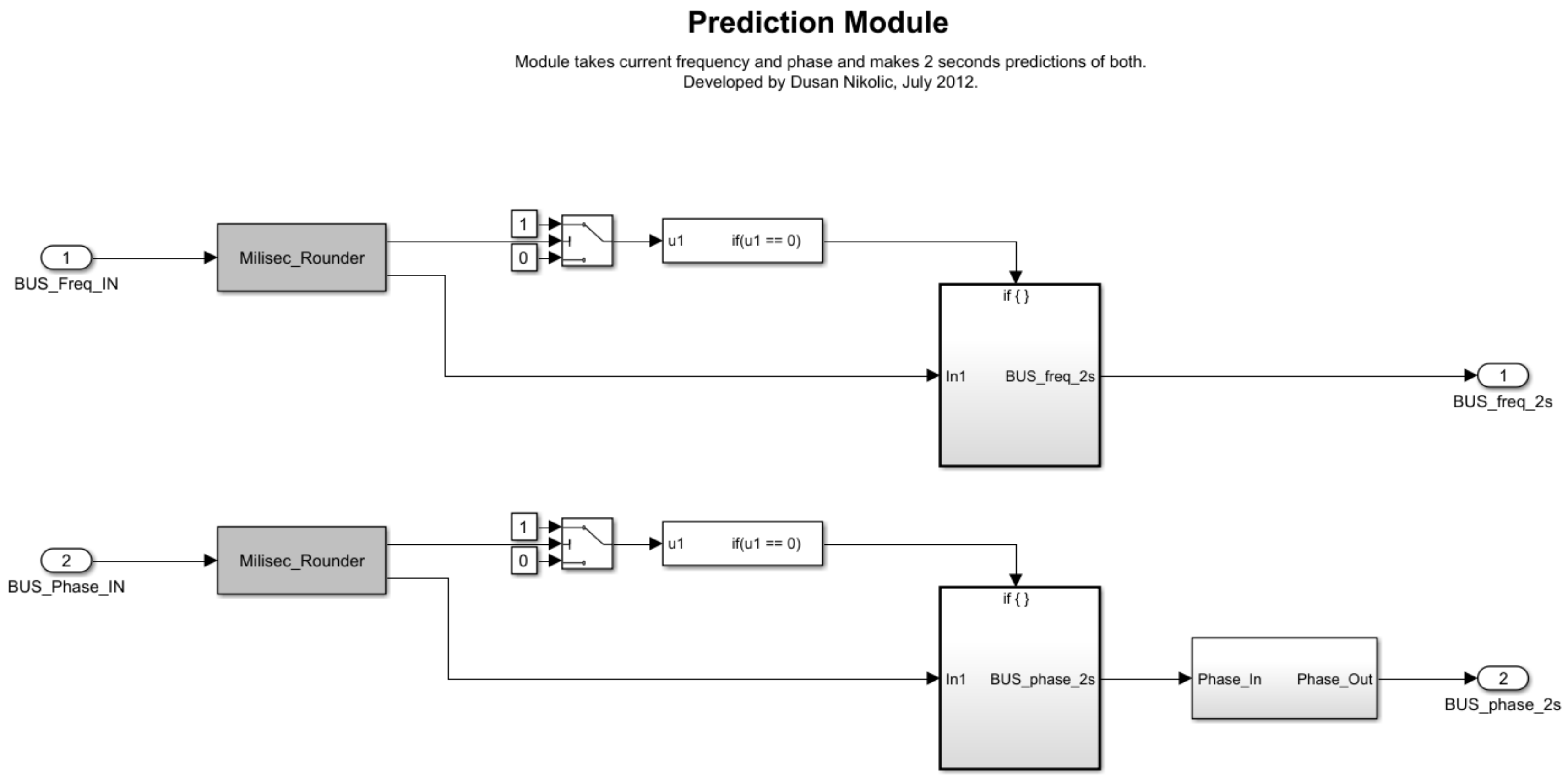

Figure A.3. Prediction Module MATLAB Simulink model. This module takes frequency and phase samples every millisecond and uses ANFIS to predict frequency and phase 2 seconds ahead.

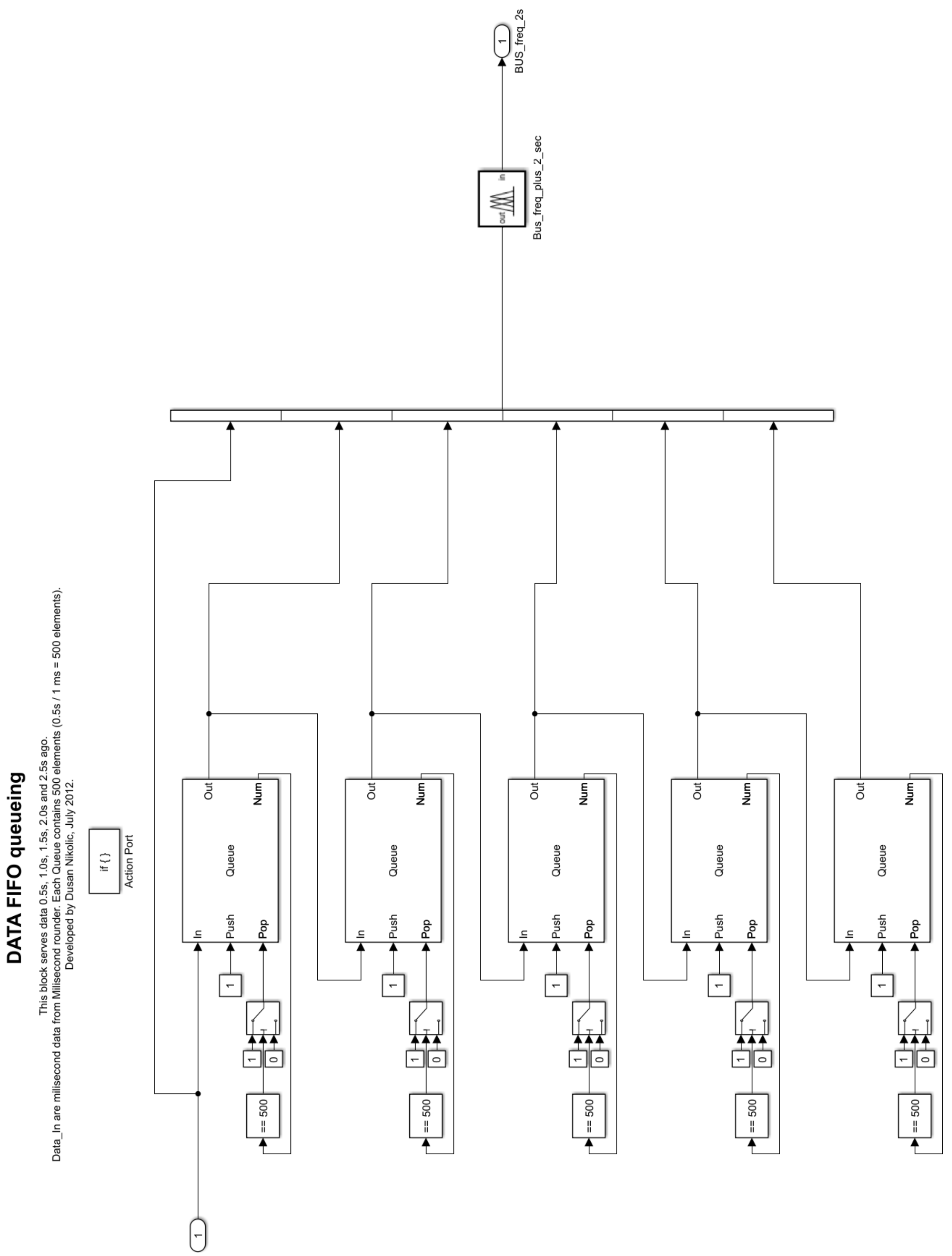

Figure A.4. Prediction Sub-Module. This sub-module takes five data samples, 500 ms apart, stores it in an array which is then served to ANFIS neural network. ANFIS predicts future value of 2,000 ms (or 2 sec) ahead.

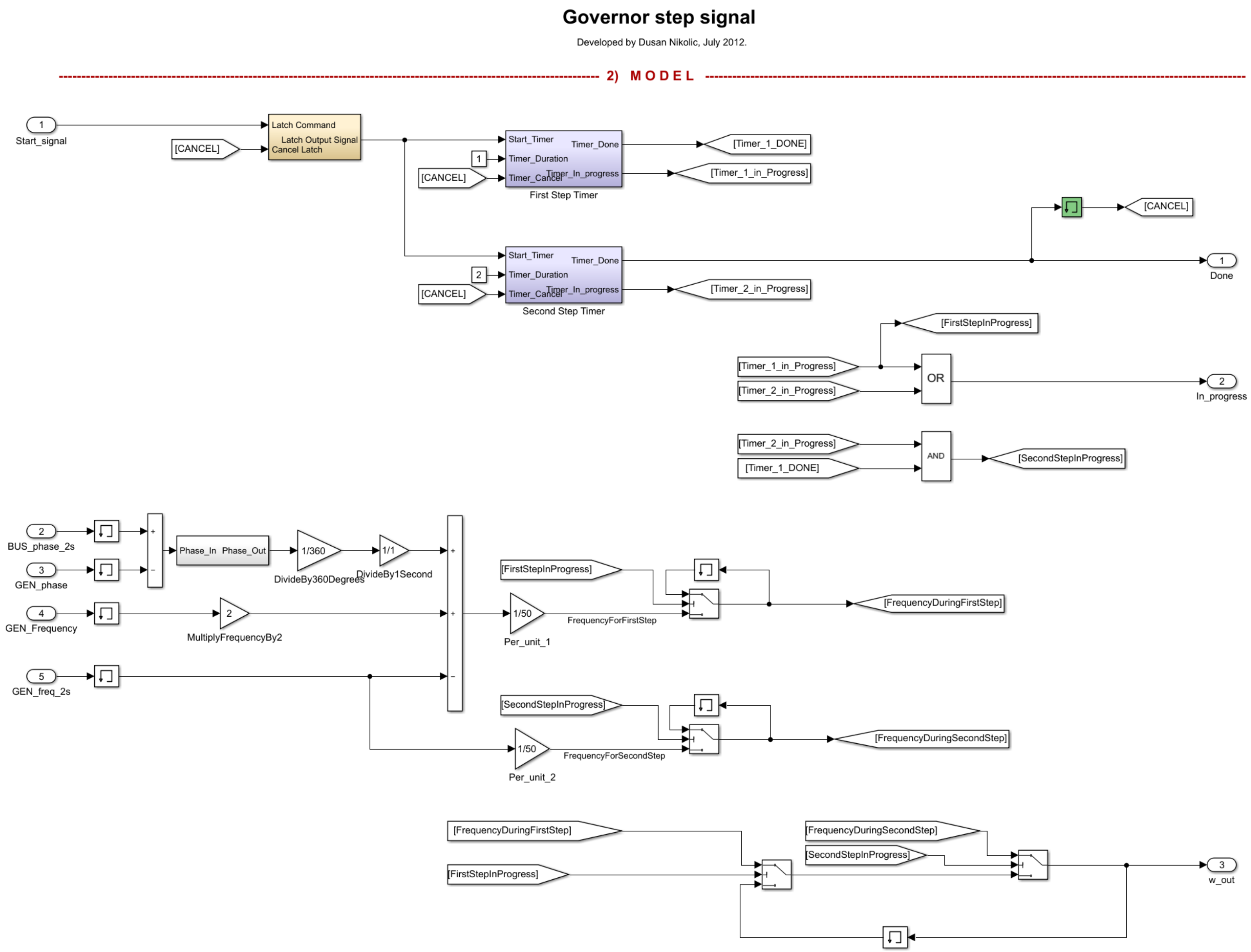

Figure A.5. Governor Step Signal MATLAB Simulink Module. When synchronisation start signal is received, this module changes the generator frequency and phase by performing two governor speed reference steps, up and down (not always in this order).

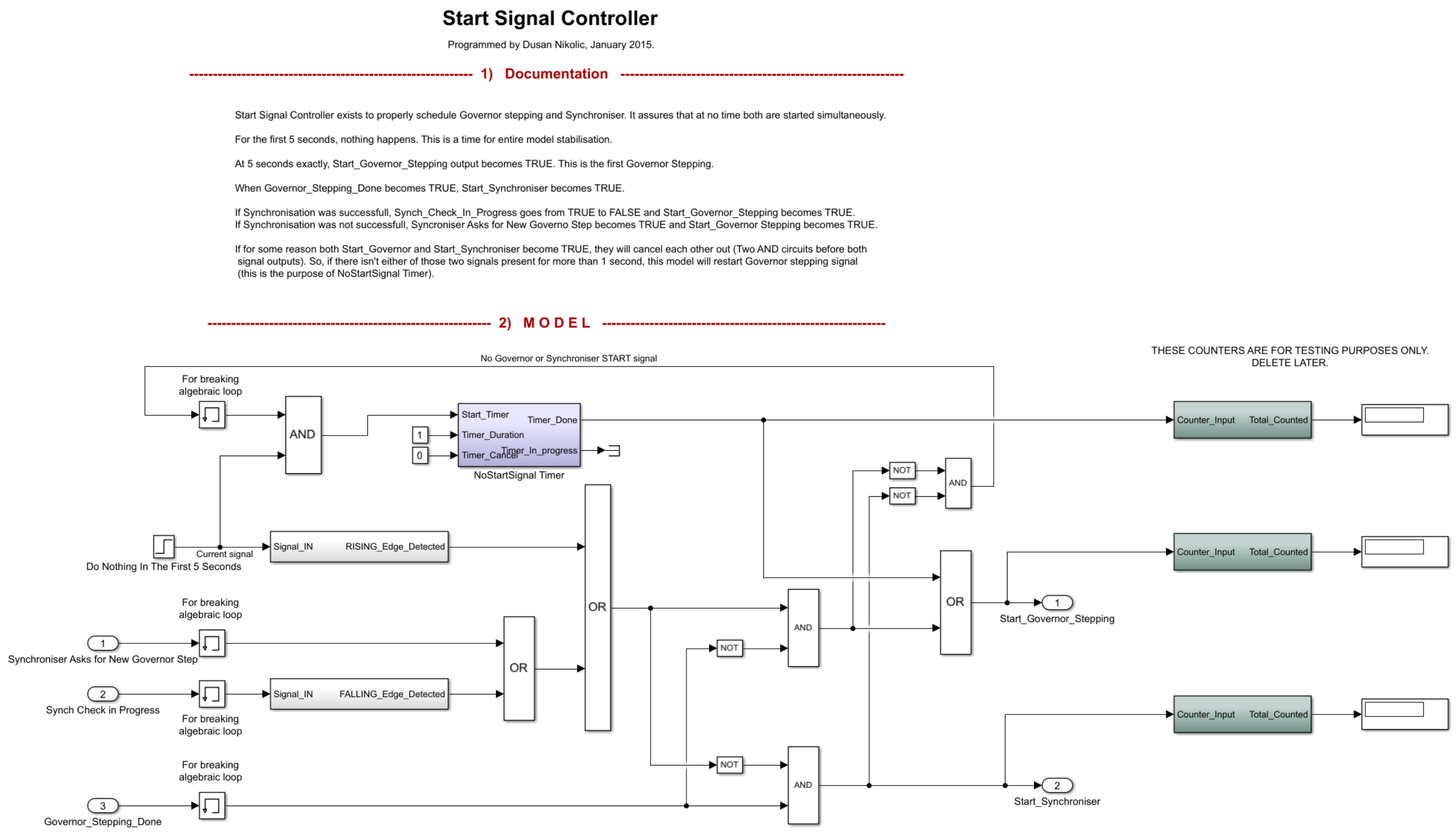

Figure A.6. Start Signal Controller MATLAB Simulink Module. This Module ensures Synchroniser is not start until Governor step signal Module has finalised its routine.

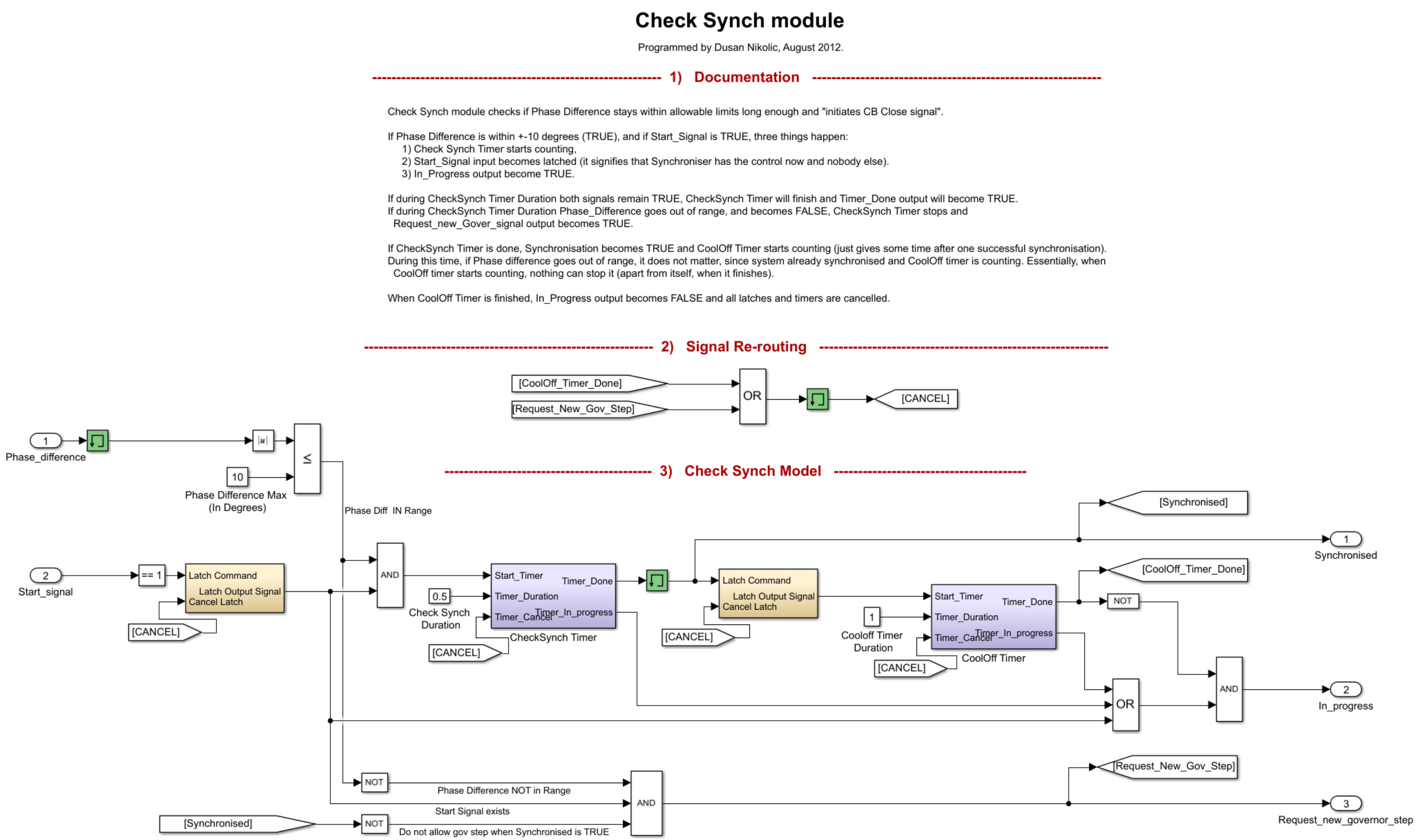

Figure A.7. Check Synch MATLAB Simulink module. This Module checks if a generator synchronised to the grid using traditional synch check method.

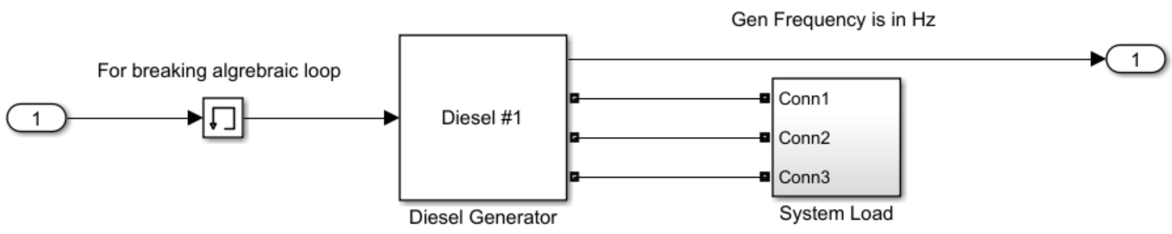

Figure A.8. Synchronising Diesel Generator MATLAB Simulink Model. ‘Diesel generator’ is a standard Simulink diesel generator model.